TFAWS Heat Pipes Short Course

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Thermal & Fluids Analysis Workshop
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Hampton, VA

Agenda

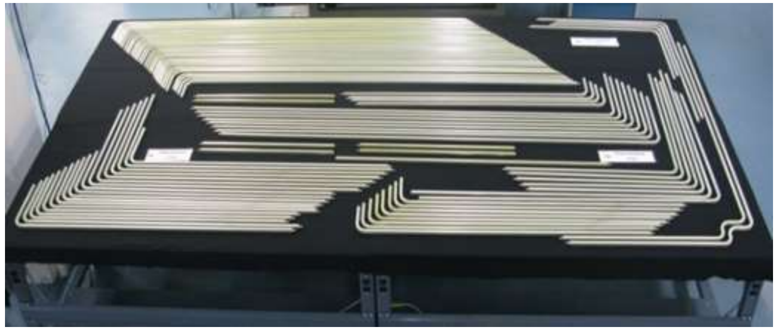
- ACT Introduction
- General Thermal Considerations
- Heat Pipe Basics
- Heat Pipe Limits
- Heat Pipe Applications
- Different Types of Heat Pipes
- Heat Pipe Working Fluids and Compatibility
- Heat Pipe Wicks
- Heat Pipe Modeling
- CCHP Design
- CCHP Manufacturing and Testing
- VCHPs for Variable Thermal Links
- Copper/Water Heat Pipe Design
- Copper/Water Heat Pipes in Space
- Copper/Water Heat Pipes in Embedded Computing
- Conclusions
- References
- Acknowledgements

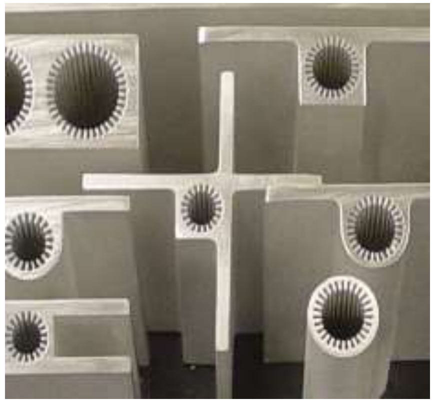
ACT Introduction

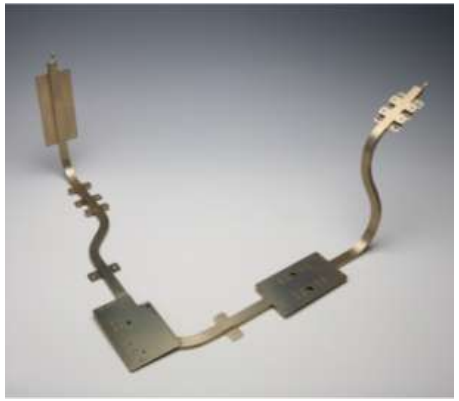
- Founded in 2003
  - Over 140 Employees
  - Over 60,000ft^2
  - ISO9001/AS9100 Certified
- Core Values
  - Innovation
  - Customer Care
  - Teamwork
- Only U.S. Company with space, ground, and high temperature heat pipes

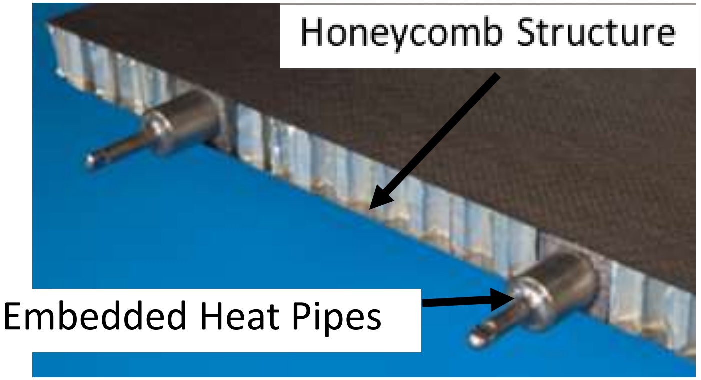
ACT Constant Conductance Heat Pipes

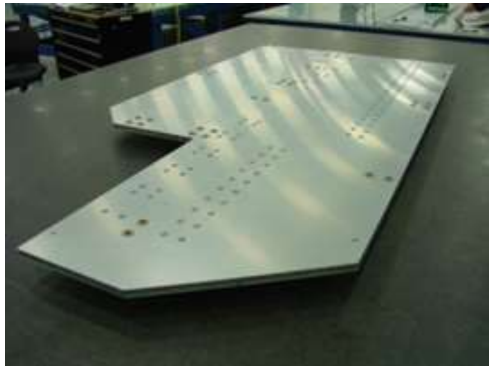
- TRL 9
- Over 36 million hours on orbit
- Designs
  - Build-to-Print and Custom
  - Embedded and External Mount
  - In house and Custom Extrusions
  - 2D and 3D Configurations
  - Integration with Radiator Panels
  - Solder Assemblies



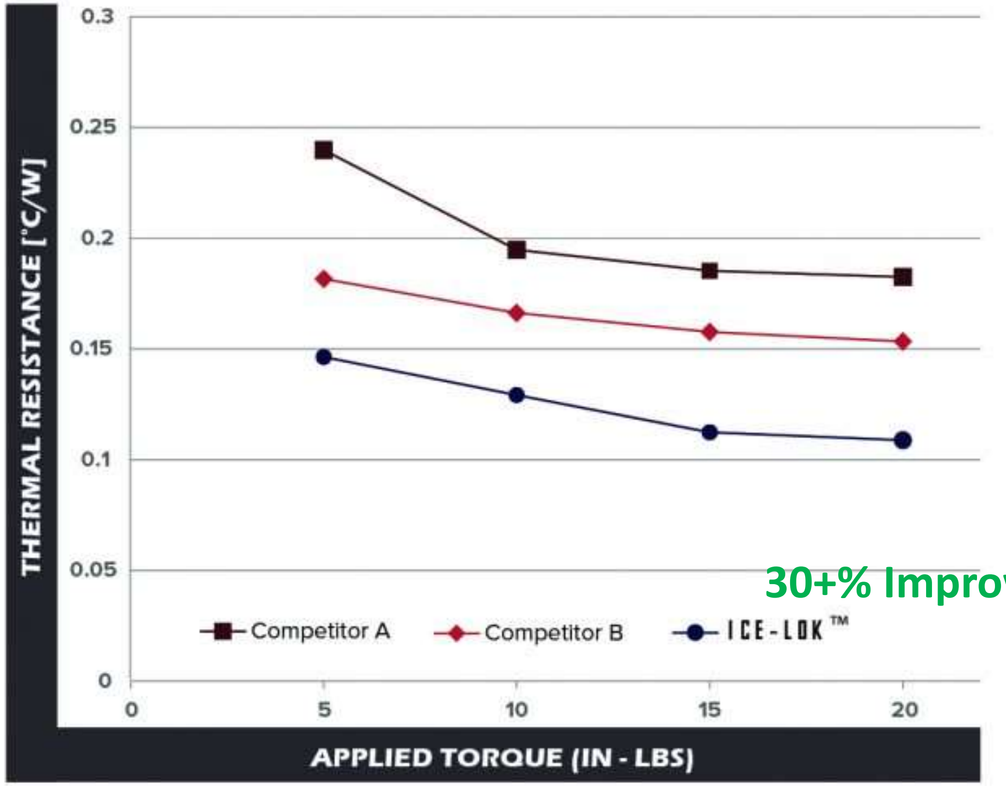




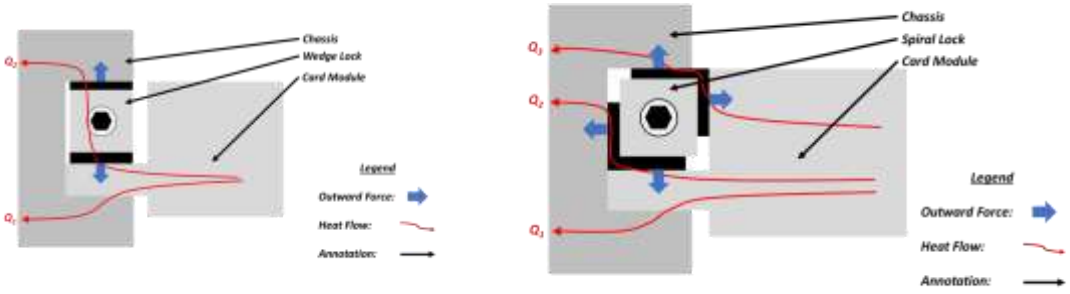




ICE-Lok™



30+% Improvement



https://www.1-act.com/products/ice-lok-thermally-enhanced-wedgelock/

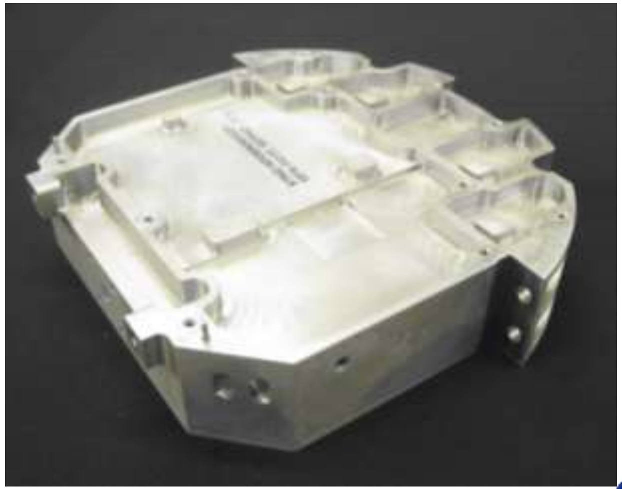
ICE-Lok™ offers additional heat transfer paths. Helps to reduce thermal gradient and lower component temperatures

Phase Change Material (PCM)

- PCM is used in short duration missions or pulsed operation
  - Reliable / passive
  - Weight and Volume Benefits

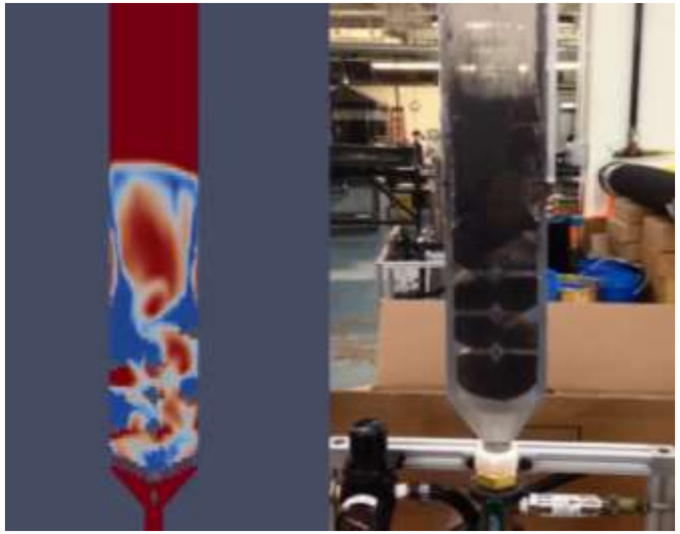
- Solid to Liquid Phase Change allows the high latent heat of the PCM to absorb and store energy

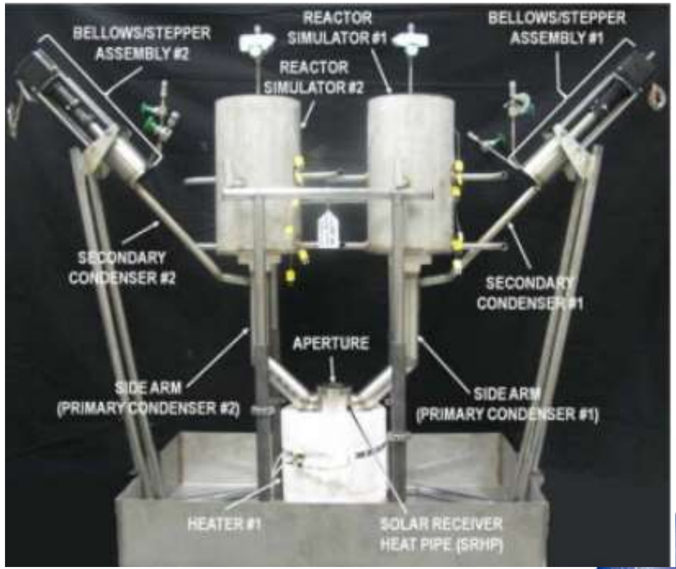
- ACT Capabilities:
  - Design/Analysis Expertise
  - Proven processing techniques
  - Developed heat exchangers/heat sinks ranging from 10s of Watts to 100s of kWs.



Research and Development

- Advanced Heat Pipes
  - PCHPs, Lightweight Titanium, Warm Reservoir VCHPs
- Vortex Phase Separators
- Swiss Roll Combustion
- Synfuels
- Vapor Venting Heat Sinks
- Custom Test Rigs
- Molecular Level Modeling
- https://www.1-act.com/innovations/





General Thermal Considerations

- Ultimate Heat Sink = Radiation (No air)
  - Radiators are more efficient at higher temperatures
  - Must operate a lower temperature than your max electronics temperature
  - Know your max component temperatures and thermal resistance network (path from electronics case to radiator)

- Reliability is key (we cannot send maintenance crews up to space!)
  - Understand the mission life
  - Avoid moving parts

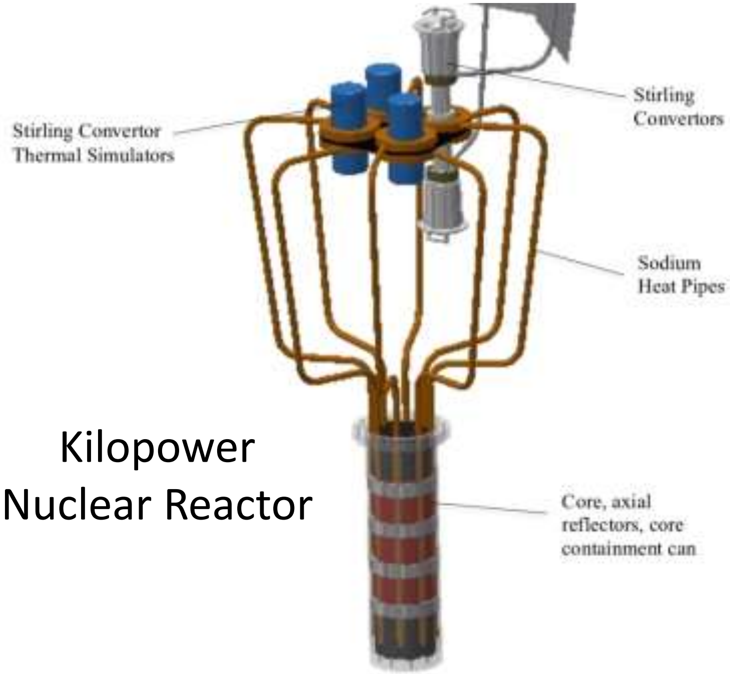
- Low mass and volume are critical

Spacecraft Overview

Lunar Lander

GEO Satellite

Cubesat



Kilopower
Nuclear Reactor

NASA Lunar
Gateway

Photos Courtesy of Astrobotic, isisspace.com and NASA

Passive Technology Options

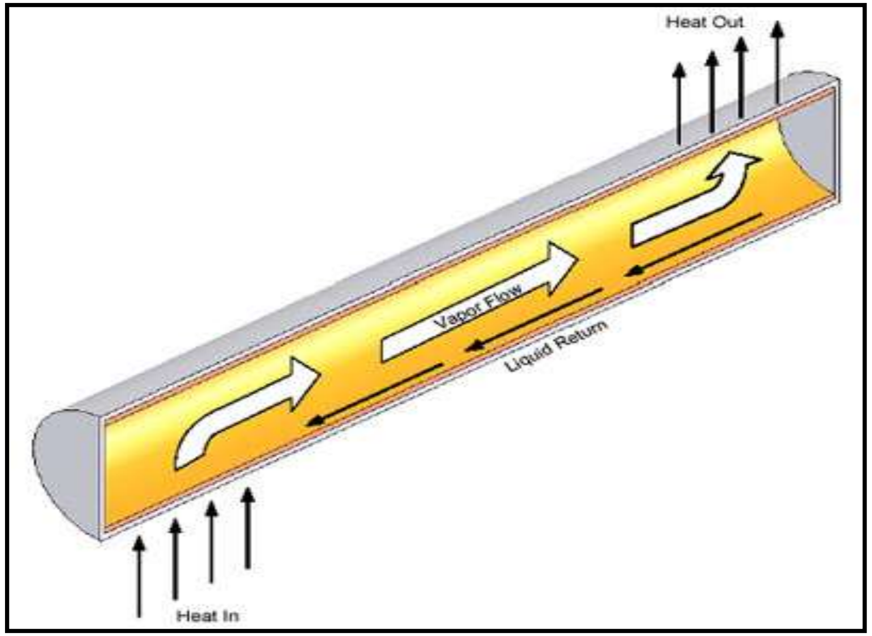
Technology	Operating Principles	When to use
Metal conduction	Conduction, k value based on material	If your thermal path is short or your allowable delta T is large
Thermal Straps	Conduction, k value based on material and pattern	Flexible connection required. Your system can allow for larger conduction gradients
Copper-Water Heat Pipes	Passive Two-Phase Heat Transfer (liquid/ vapor)	Board and Box level heat transfer.
Aluminum-Ammonia Heat Pipes	Passive Two-Phase Heat Transfer (liquid/ vapor)	System level heat transfer
Other fluid Heat Pipes	Passive Two-Phase Heat Transfer (liquid/ vapor)	Non traditional operating temperatures
Phase Change Material (PCM)	Utilizes high latent heat of fusion of two-phase transition (solid/liquid)	Thermal absorption for duty cycle applications

Heat Pipe Basics

- What is a Heat Pipe?
- When is a Heat Pipe Used?
- Heat Pipe Operating Principles
- Heat Pipe Zones
- Vapor Flow
- Gravity

What is a Heat Pipe?

- A Heat Transfer Device That Requires No External Power For Its Operation
- Transfers Heat With Very Low Loss of Temperature
- Uses a "Working Fluid" That Is Vaporized And Carries The Power and a Capillary Pump, the Wick, That Returns the Liquid
- A Heat Pipe is a Pressure Vessel That Must Resist Both Internal and External Pressures
- It is Evacuated and Sealed – Only the Working Fluid and its Vapor – No Air
  - Air interferes with vapor flow in the heat pipe

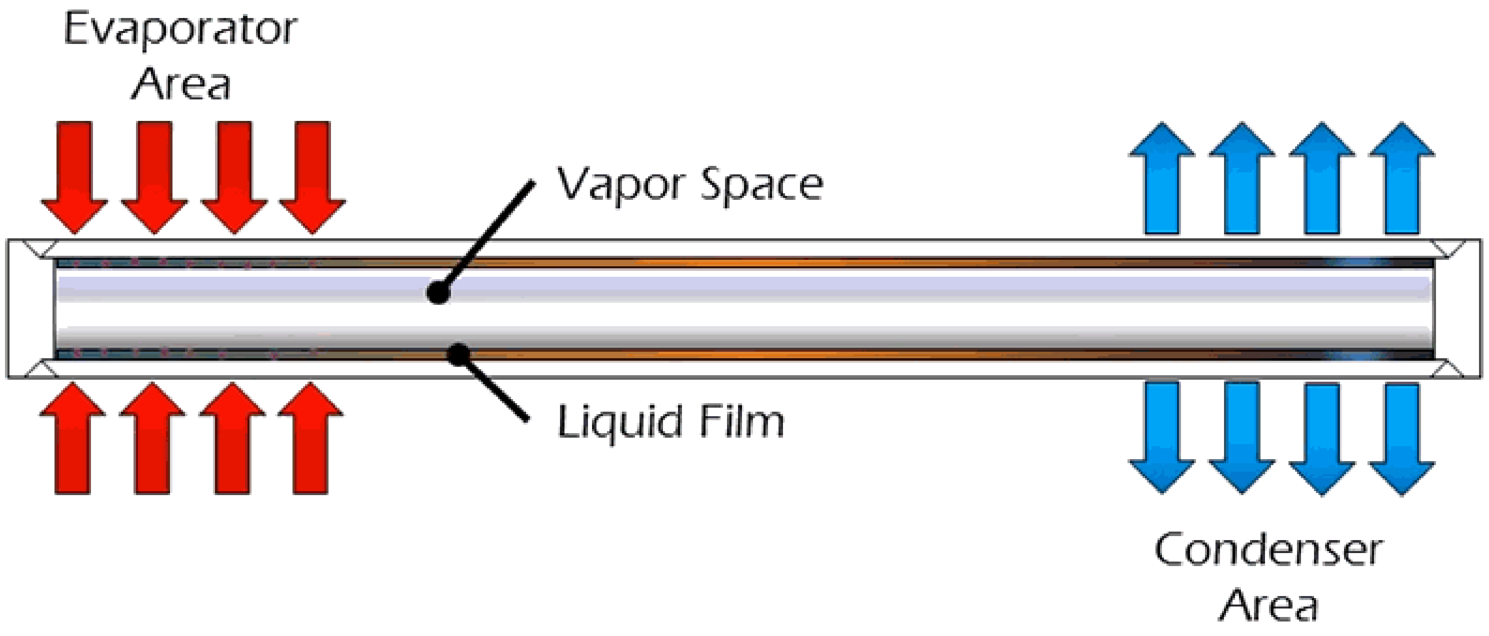


Key Words

Passive, "Superconductor", Two-Phase
Vacuum Leak Tight, Pressure Vessel

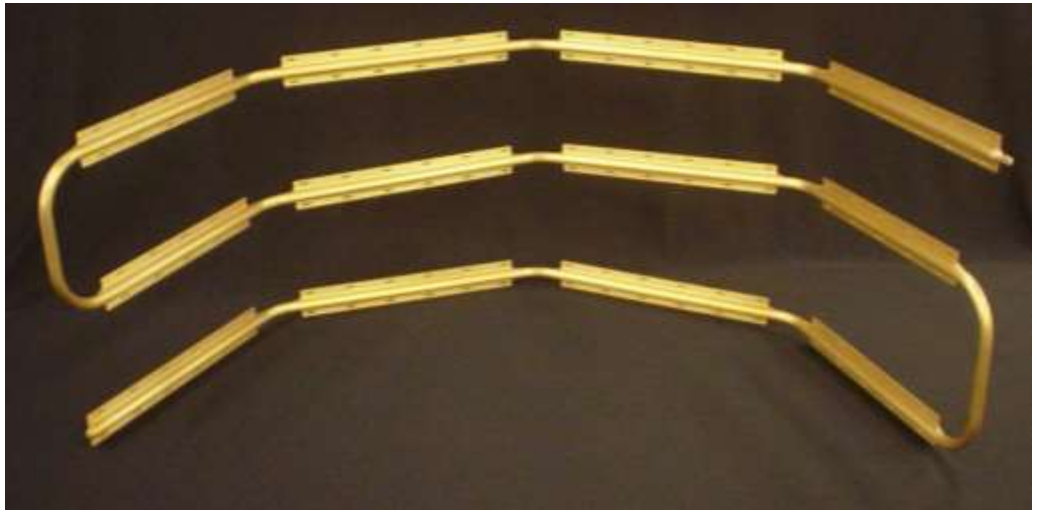
Heat Pipe Principles

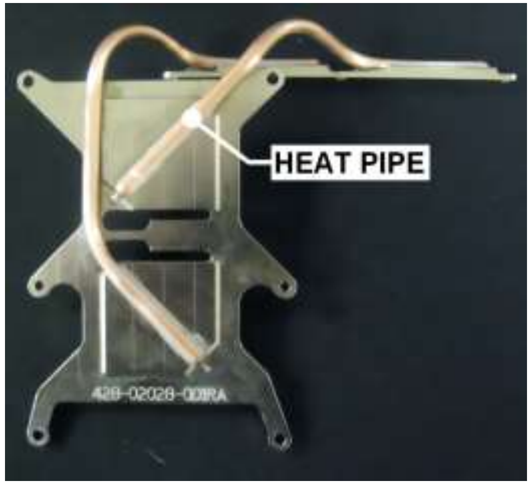
- Passive two-phase heat transfer device operating in a closed system
  - Sealed Vacuum Metal Tubes with only a working fluid and a wick structure inside
  - Operates when subjected to a Temperature Difference (ΔT)
  - Heat/Power causes working fluid to vaporize at the hot evaporator
  - Vapor flows to cooler end where it condenses
  - Condensed liquid returns to evaporator by gravity or capillary force
  - Typically 2-5°C ΔT across the length of the heat pipe

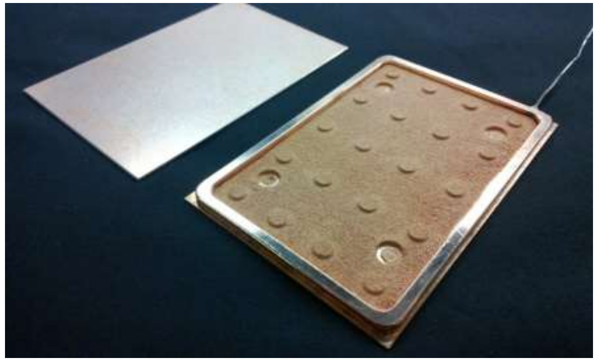


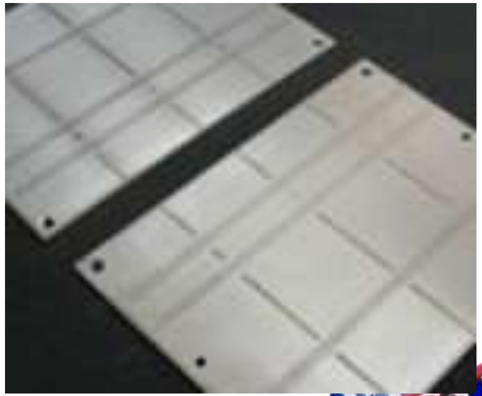
When are Heat Pipes Used

- Heat pipes are used for 3 reasons
  - Transport heat from a to b
    - Heat Pipes, HiK™ Plates, Vapor Chambers
  - Isothermalization
    - HiK Plates, Vapor Chambers
  - Heat flux transformation
    - Vapor Chambers



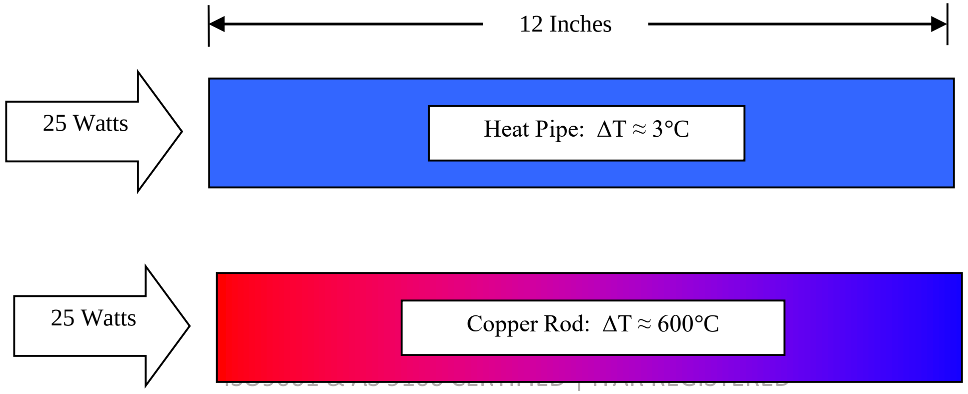




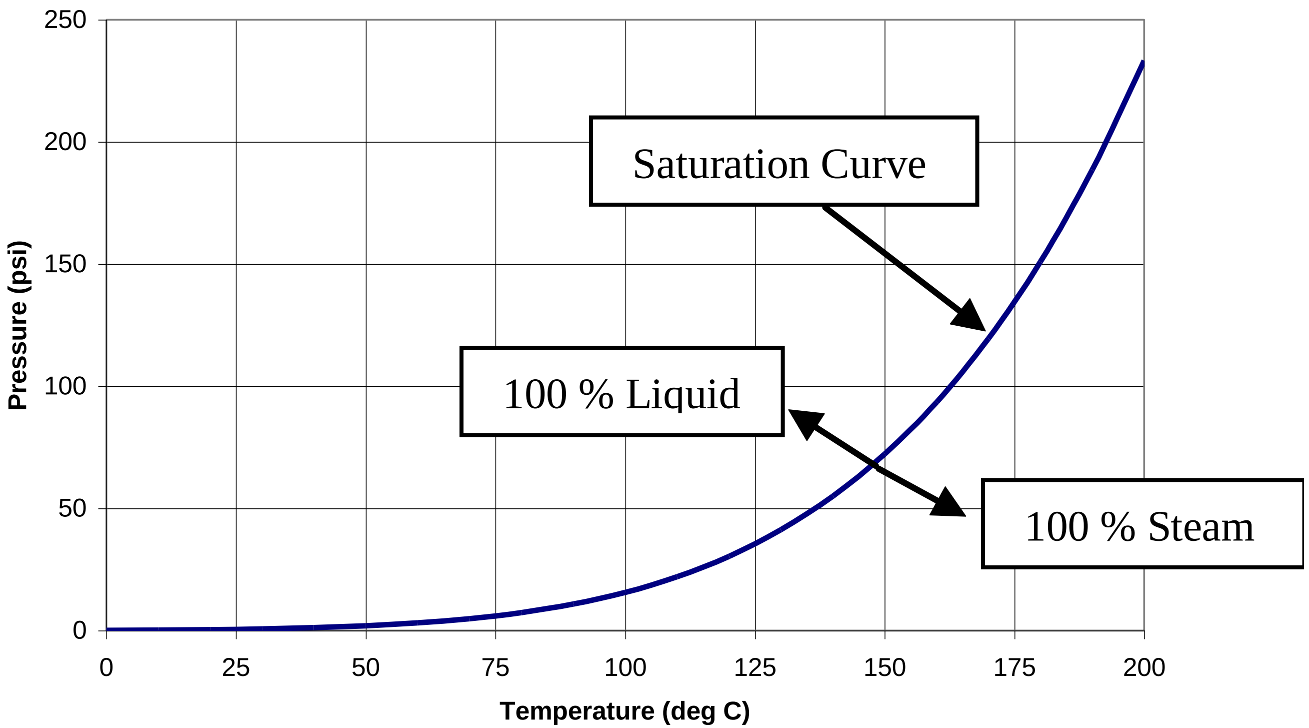


The Heat Pipe is a "Superconductor" of Heat

- From the conduction equation - ΔT = QL/kA   Where:
  - Q = Thermal Power (Watts) = 25 Watts
  - L = Rod Length (m) = 12" = 0.305m
  - K = Thermal Conductivity (W/m-°C); Copper = 400 W/m-K
  - A = Cross Sectional Area of Rod (m2) = πD2/4 = π*.252/4 in2 or 3.17x10-5 2
  - ΔT = Temperature Difference along Rod Length (°C)
- For the solid copper rod, the temperature difference along the rod is:
  - ΔT = (25W * .305m)/(400W/m-°C * 3.17x10-5 m2) ≈ 600°C
- Copper Water Heat Pipe has ΔT ~ 3°C
  - Effective thermal conductivity is approximately 80,000 W/m-°C
  - ΔT = (25W * .305m)/(80,000W/m-°C * 3.17x10-5 m2) ≈ 3°C



How Does a Heat Pipe Operate?



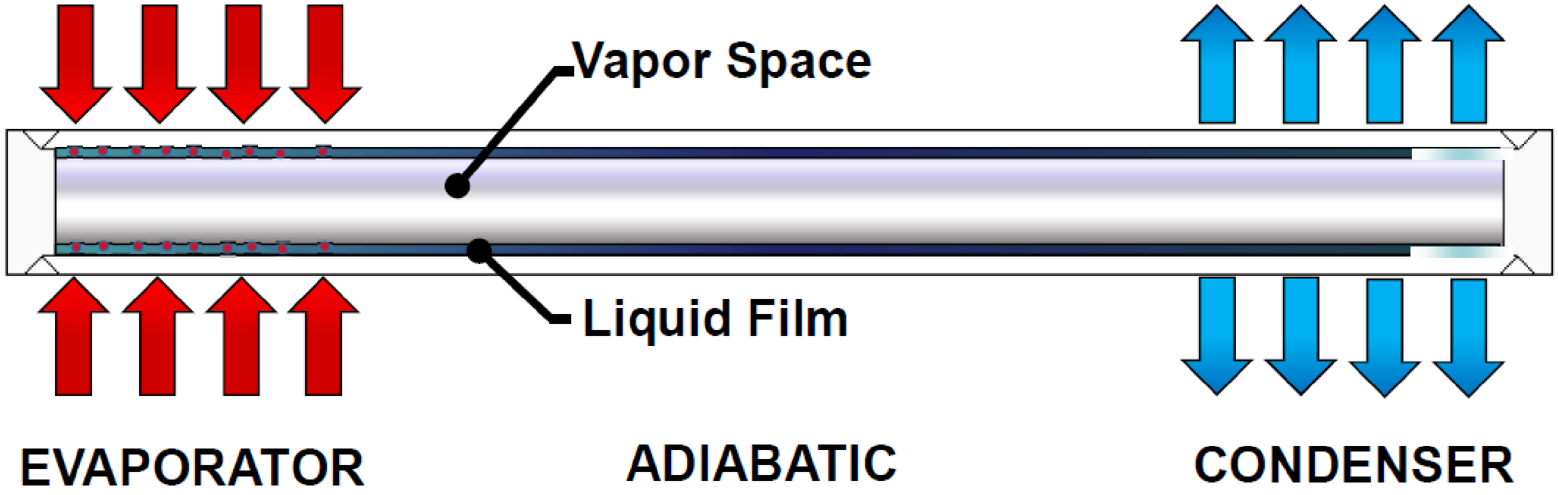
- Vacuum Tight Pressure Vessel - Heat pipes operate on the **Saturation Curve** since both liquid and vapor exist at the same time inside of a heat pipe. The pressure is also the **Saturation Curve** pressure.

Heat Pipe Basics

- Working fluid exists at saturation within the heat pipe
  - No other species is present in appreciable amounts
    - Prior to filling, heat pipe is brought under vacuum
    - Processing procedures ensure fluid and material purity
  - Can operate over entire liquid-vapor temperature range
    - Between freezing and critical temperatures
  - Internal pressure corresponds to vapor pressure at temperature
  - Envelope is designed to withstand pressure at highest temperature
- Expected operating temperature range determines potential working fluids
- Heat pipe temperature is driven primarily by source and sink conditions
  - Heat transfer conductance
  - Temperature

Heat Pipe Zones

- Evaporator (The Heat Input Zone)
- Adiabatic (The Part of the Heat Pipe Length Between the Evaporator and Condenser Zones). In the Adiabatic Zone, There is Little Heat Loss to the Outside of the Pipe
- Condenser (The Heat Output Zone)

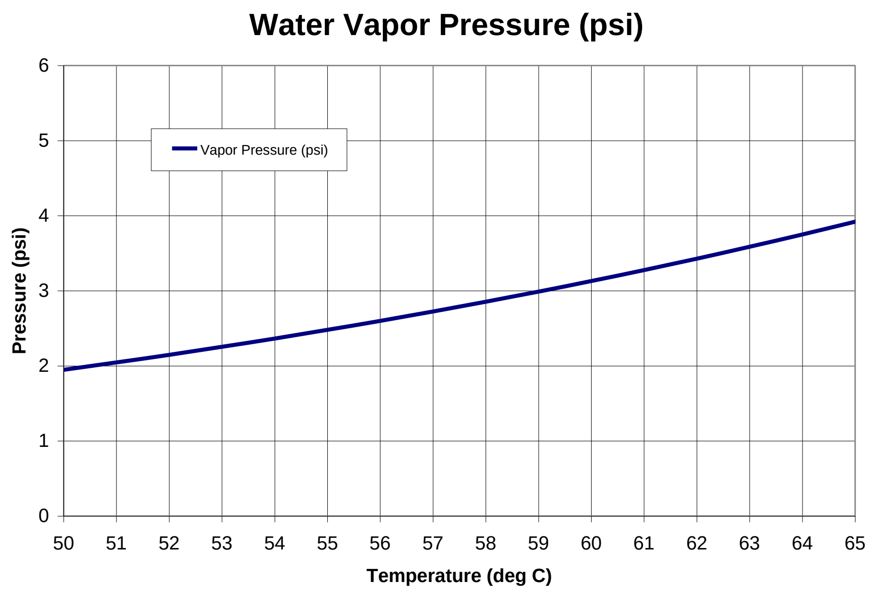


Heat Pipe Operation – More Details

- Heat Transfer
  - Conduction Through Wall & Wick
  - Evaporation of Working Fluid
  - Vapor Flow
  - Condensation
  - Conduction Through Wall & Wick
- The Higher the Power per Area (Heat Flux), the higher the ΔT
- Almost all of the ΔT is in the wall/wick conduction
- Roughly 2-5°C ΔT in the vapor under normal operating conditions

Vapor Flow

- The liquid temperature is slightly hotter in the evaporator than the condenser
- As a result, the vapor pressure is slightly higher in the evaporator than the condenser
- The pressure difference causes the vapor to flow from evaporator to condenser, carrying the heat with it

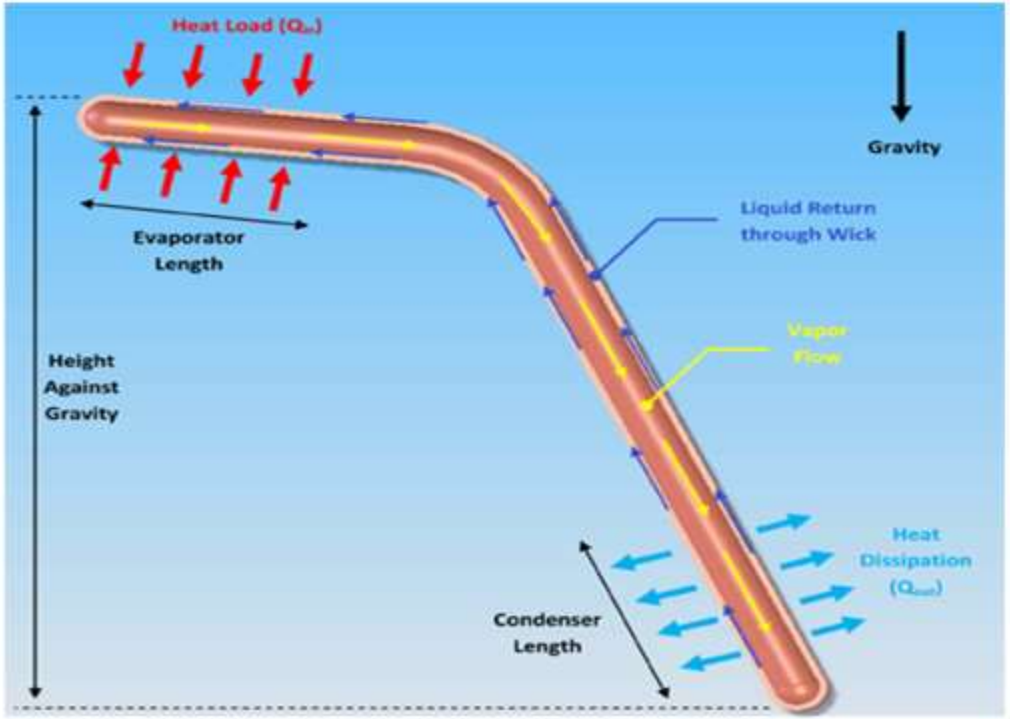


Vapor Space Considerations

- Vapor velocity is high – often several hundred mph & approaching the speed of sound. For reference, liquid flow is about walking speed
- When operating at the cold end of the saturation curve – the total available pressure (saturation pressure – zero) may be so small that sufficient vapor flow cannot be driven (the viscous limit)
- High velocity vapor may create a shock wave (the sonic limit), which reduces vapor flow & power, also creates very high delta-t in the pipe
  - Many pipes, especially liquid metal pipes pass through the viscous and sonic limits naturally as they warm-up
- High vapor velocity can entrain droplets of liquid flowing on the surface of the wick (entrainment limit).
  - Sometimes this is audible as a clicking or pinging sound when the entrained droplets hit the condenser wall
- The vapor space is kept large to keep the velocity down, often 2/3 of the pipe inner diameter

Heat Pipe Design Input

- Power
- Temperature Range
  - Operating
    - Determines Allowable Fluids and Materials
  - Non-operational
    - May need to consider freezing at low temperatures
    - Design envelope to withstand pressure at highest storage temperature
- Length, Orientation, Acceleration
  - Sets maximum hydrostatic force
  - Determines allowable wick designs
- Bends, other constraints



Heat Pipe Basics Takeaways

- Heat Pipes are thermal "superconductors"
  - Effective Thermal Conductivities of 10,000 to 100,000 W/m K
- Heat pipes are used for 3 reasons
  - Transport heat from a to b
  - Isothermalization
  - Heat flux transformation
- Heat Pipes have 3 zones
  - Evaporator – Heat Addition
  - Adiabatic Zone – No Heat Transfer
  - Condenser – Heat Removal
  - Spacecraft heat pipes often have multiple evaporators and condensers
  - Evaporator can also act as condenser, and vice-versa

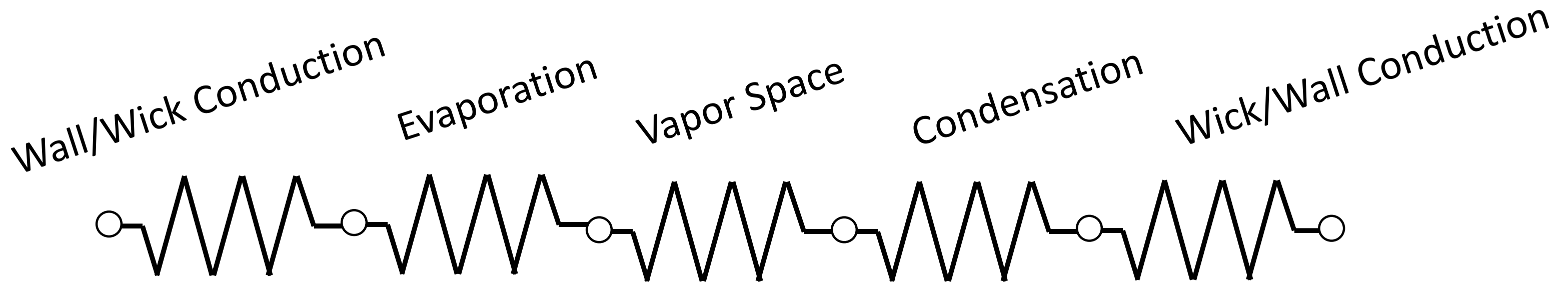
Heat Pipe Limits

- Heat Pipe Operating Temperatures
- Heat Pipe Limits
- Capillary Pumping Capability
- Capillary Limit

Heat Pipe Operating Temperatures

- Heat pipes do not have a set operating temperature
  - In general, a copper water heat pipe does NOT operate at 100°C
- Hard Limits: Triple and Critical Points
  - Water: 0.01°C Triple Point to 373.9°C Critical Point
- Practical Limits for Water
  - ~25°C at low end (sonic limit at lower temperatures)
  - ~150°C for copper (yield strength of copper vs. saturation pressure)
  - ~300°C for Monel and titanium (declining surface tension and latent heat)
- Heat pipe operating temperature set by thermal resistances into and out of the heat pipe
- Heat Pipe is designed so that the power is also set by the thermal resistances
- Design so heat pipe limits are higher

Heat Pipe Operating Temperatures



$$\frac{ln\left(\frac{r_o}{r_i}\right)}{2\pi l_e k} \qquad \frac{1}{2\pi r_i l_e h_e} \qquad \frac{l}{\pi {r_i}^2 k_{eff}} \qquad \frac{1}{2\pi r_i l_c h_c} \qquad \frac{ln\left(\frac{r_o}{r_i}\right)}{2\pi k l_e}$$

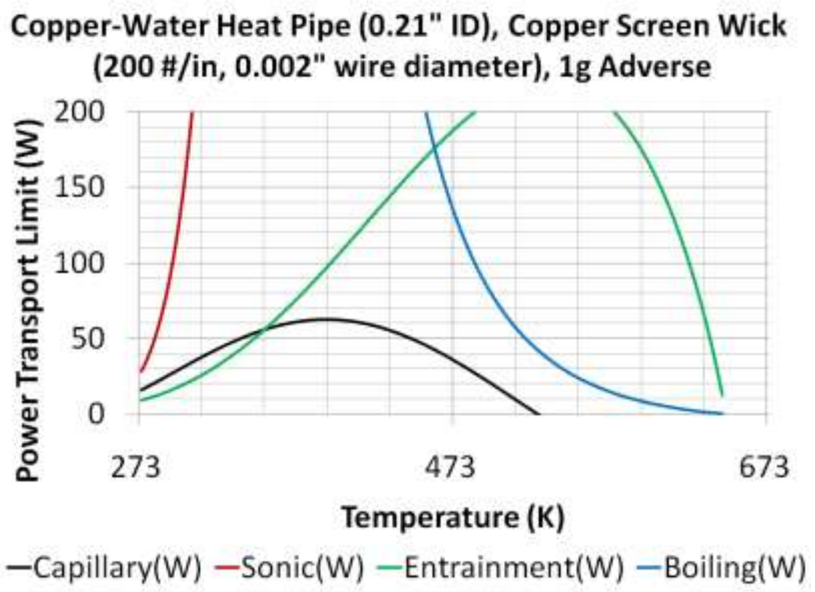
- In a properly designed heat pipe, the maximum power is set by the source and sink conditions.
- Conduction through the envelope wall and wick
- Evaporation
- Vapor Space Temperature Drop
- Condensation
- Conduction through the envelope wick and wall
- Additional ΔTs to bring the heat to the evaporator, and reject the heat from the condenser

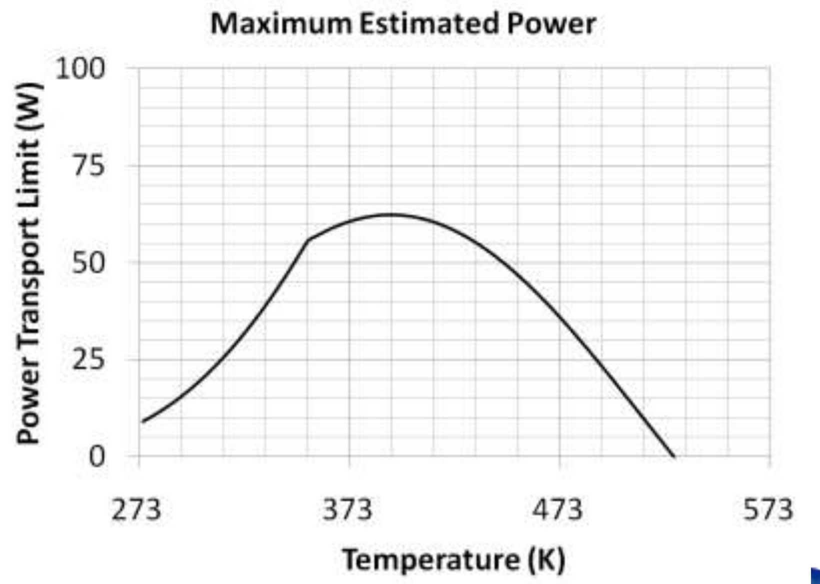
Heat Pipe Limits

- There are four heat pipe limits of interest
  - **Capillary Limit** – Wick can no longer transport liquid at a high enough flow rate to support evaporation rate.
    - Affected by wick structure, fluid properties, and acceleration environment
  - **Entrainment Limit** – Vapor flowing from the evaporator is of sufficient velocity to shear liquid from the wick, which results in a reduction of liquid flow returning to the evaporator.
  - **Sonic Limit** – The vapor flow becomes choked and cannot achieve a higher velocity.
    - Seen in alkali metal heat pipes during start-up
  - **Boiling Limit** – The heat flux is sufficient to cause vapor bubbles to form inside the wick. This limits liquid return flow and produces hot spots in the wick structure.
  - https://www.1-act.com/resources/heat-pipe-performance/

Heat Pipe Limits

- Operating limits are estimated and compared against design requirements
- Parameters are adjusted until design meets requirements
- Test heat pipes are fabricated to validate operating limits
- The example to the right demonstrates a copper-water heat pipe operating against gravity
- Entrainment and capillary limits restrict the maximum power
  - Based on theoretical models

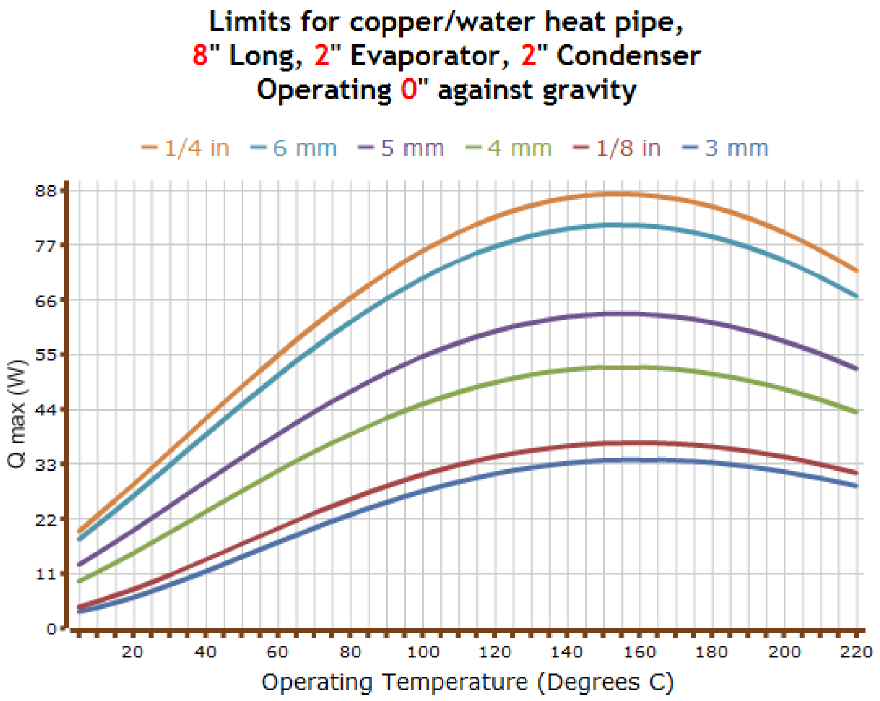




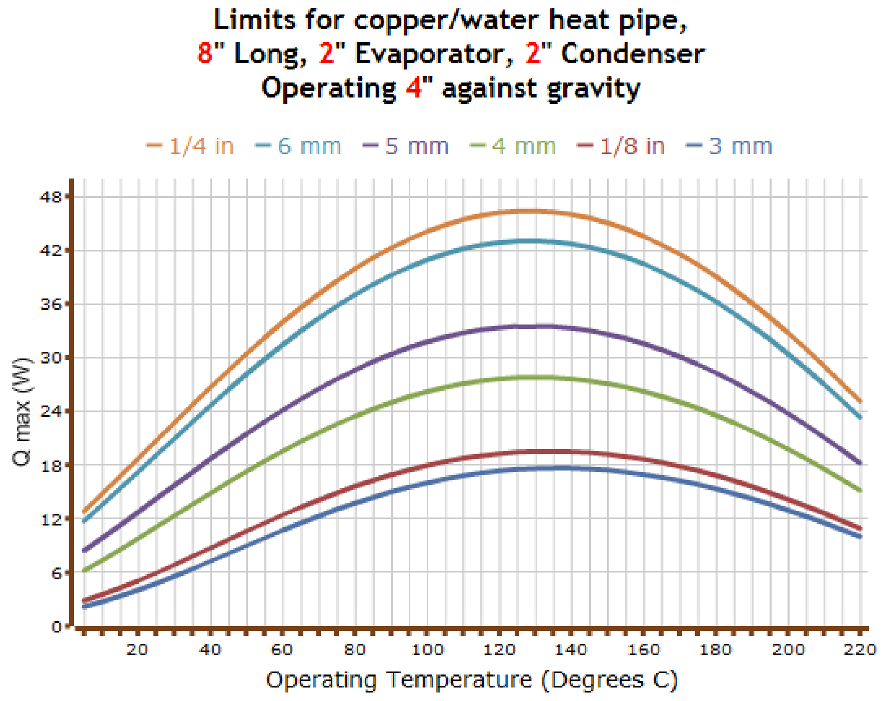
Heat Pipe Limits - Gravity

- Gravity reduces heat pipe maximum power
- 10 in. (25 cm) maximum adverse elevation for copper/water heat pipes
- 0.1 in. (2.5 mm) maximum adverse elevation for grooved Al/NH_3 heat pipes

Horizontal



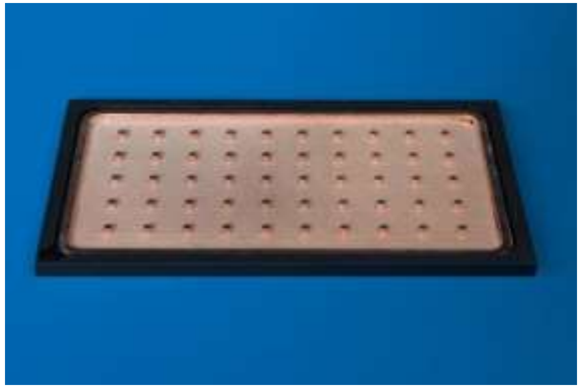
4” Against Gravity



Capillary Pumping

- Liquid condensate is returned to the evaporator by a capillary pump, also known as a wick
- Capillary pumping pressure is highest when the pores in the wick are small
- Permeability (hydraulic conductance) is highest when the pores are large, so there's a tradeoff in wick design

Axial Grooves



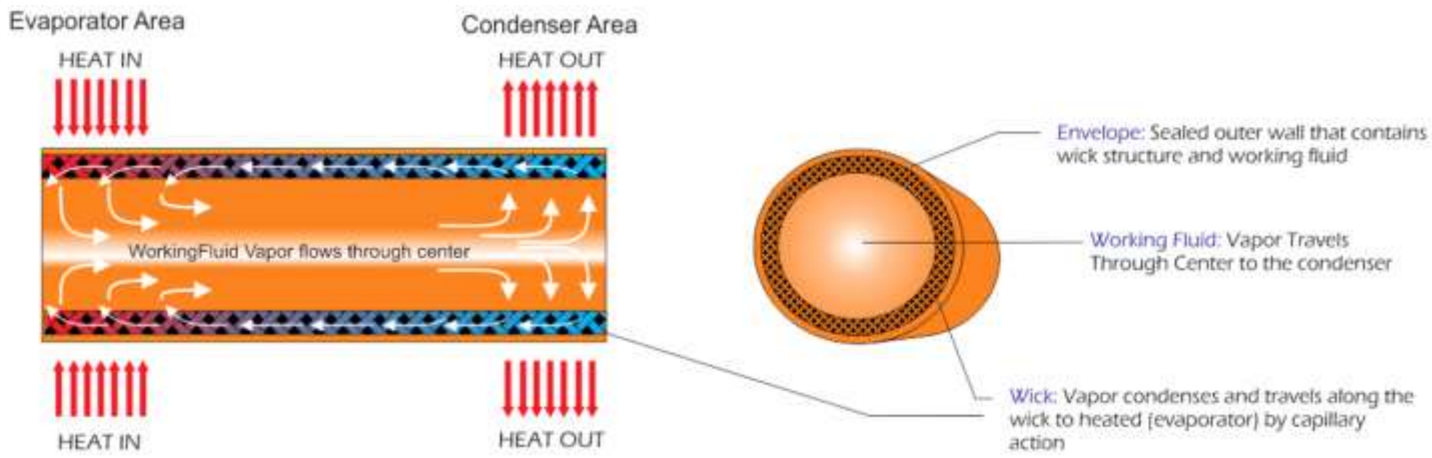
Screen Mesh

Sintered Powder

Capillary Limit

$$\Delta P_c \geq \Delta P_g + \Delta P_V + \Delta P_L$$

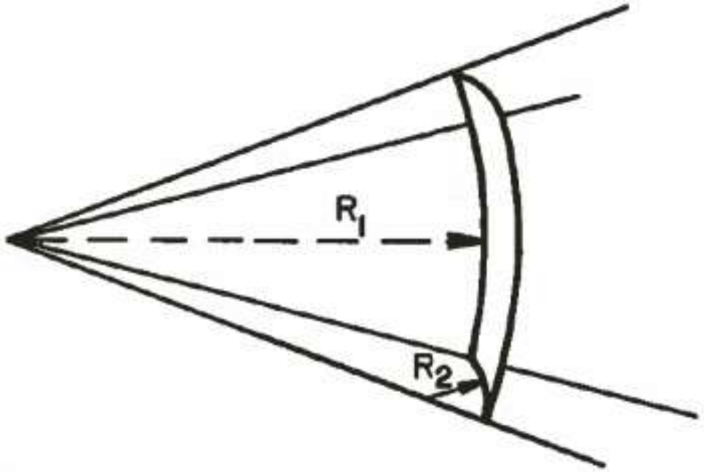
- ΔP_c Capillary force generated in the wick, Pa
- ΔP_g Pressure drop due to gravitation and acceleration, Pa
- ΔP_L Liquid pressure drop in the wick, Pa
- ΔP_V Vapor pressure drop in the heat pipe, Pa



ΔP_c – Capillary Force

- Capillary Pumping Capability Depends on the surface tension and the two radii of curvature, measured perpendicular to each other:

$$\Delta P_c = \sigma \cdot \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$$



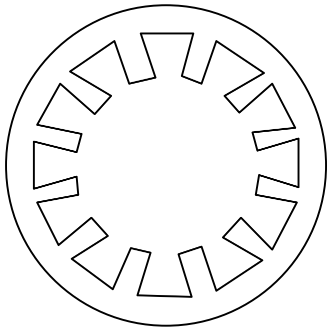
- For sintered and screen wicks, this reduces to:

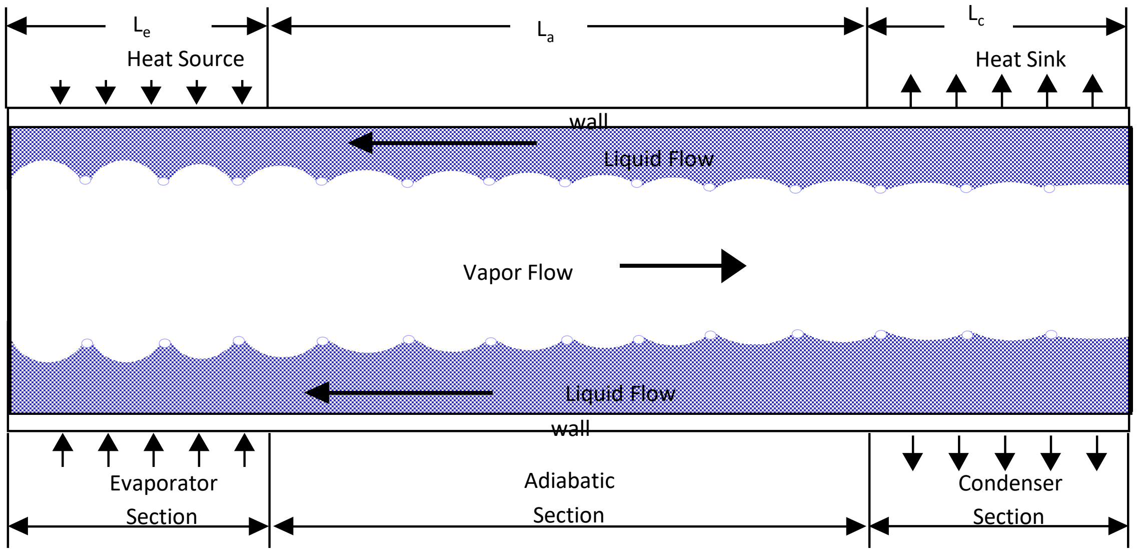
$$\Delta P_c = \frac{2 \cdot \sigma}{r_c}$$

- For grooves, one of the radii is infinite, so the equation reduces to:

$$\Delta P_c = \frac{\sigma}{r_{groove}} = \frac{2 \cdot \sigma}{Width_{groove}}$$

Pressure Differential at Liquid Vapor Interface





- The vapor pressure decreases as it flows from the evaporator to the condenser.
- The liquid pressure decreases as it flows from the condenser to the evaporator.
- At any cross section of the heat pipe, a pressure differential exists between the vapor and liquid phases. This delta pressure is sustained by the surface tension force developed at the liquid/vapor interface at the tip of each groove.
- The lowest delta pressure occurs at the very end of the condenser (zero). The highest delta pressure occurs at the very end of the evaporator.

Taken from Introduction to Heat Pipes - Ku 2015 TFAWS

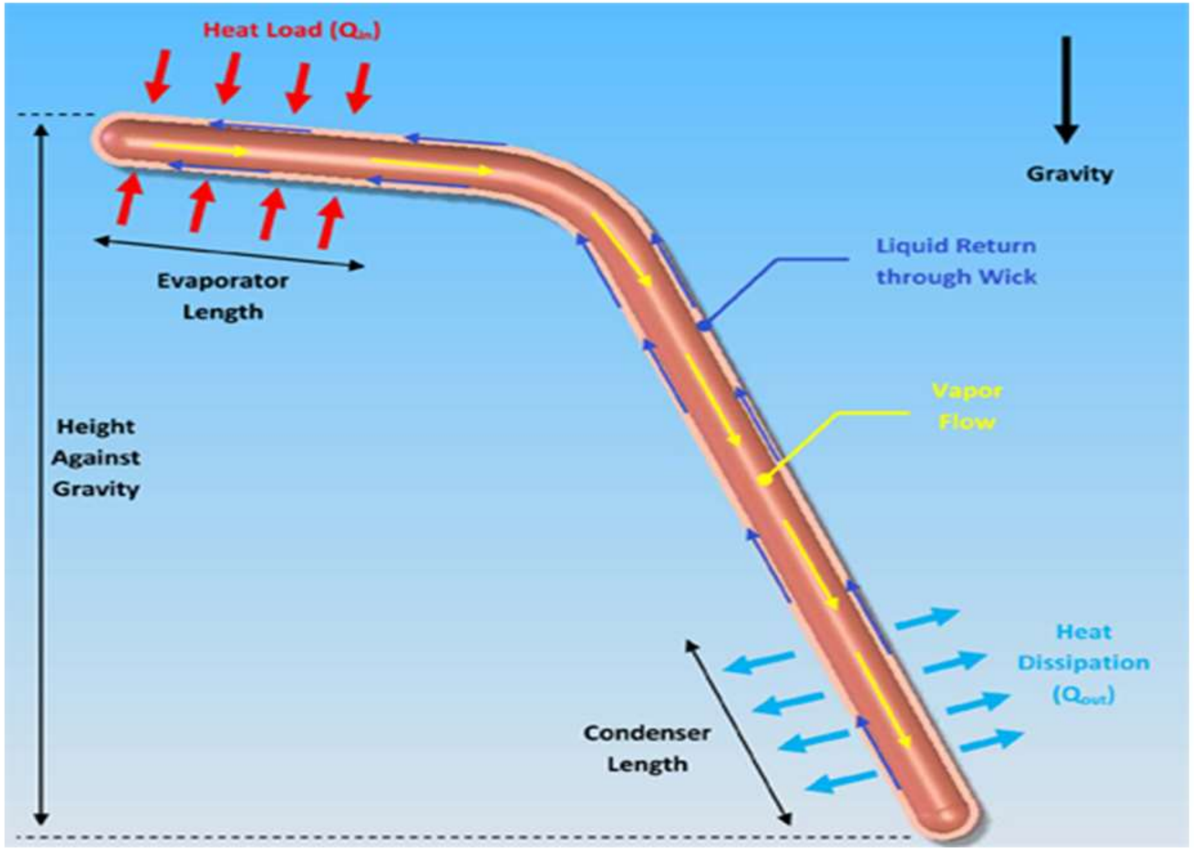
ΔP_g Gravitational Pressure Head

$$\Delta P_g = (\rho_L - \rho_V) \cdot g \cdot h$$

- Since $\rho_V << \rho_L$ this becomes

$$\Delta P_g = \rho_L \cdot g \cdot h$$

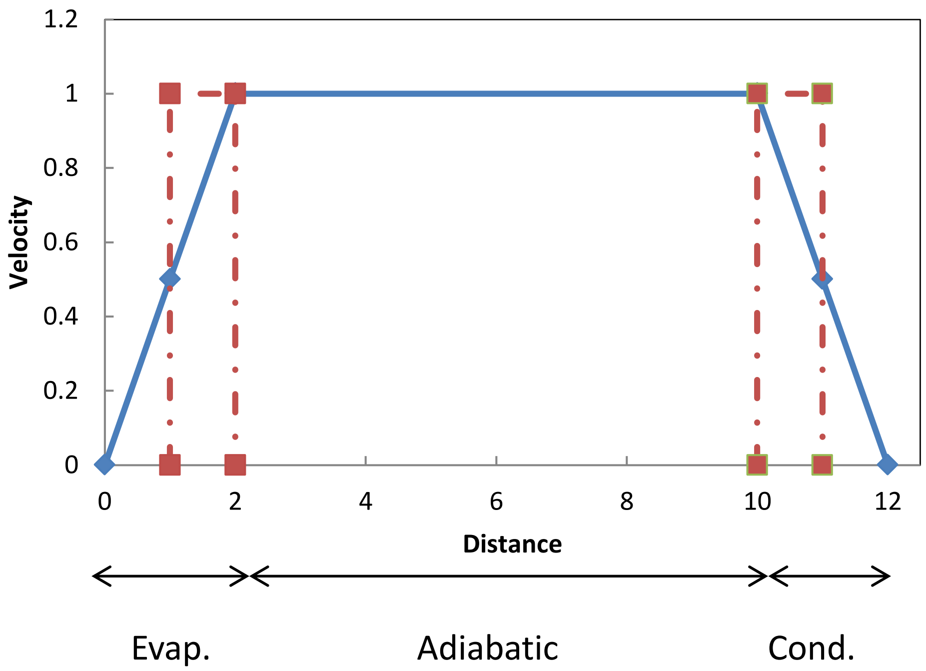
- h is the overall height of the tilted pipe, including the tilted diameter
- True except for (most) grooved pipes



Effective Length

- Effective Length used in Vapor and Liquid Pressure Drop Calculations
  - Flow Rates increase in evaporator, decrease in condenser

$$L_{Effective} = \frac{L_{Evaporator}}{2} + L_{Adiabatic} + \frac{L_{Condenser}}{2}$$

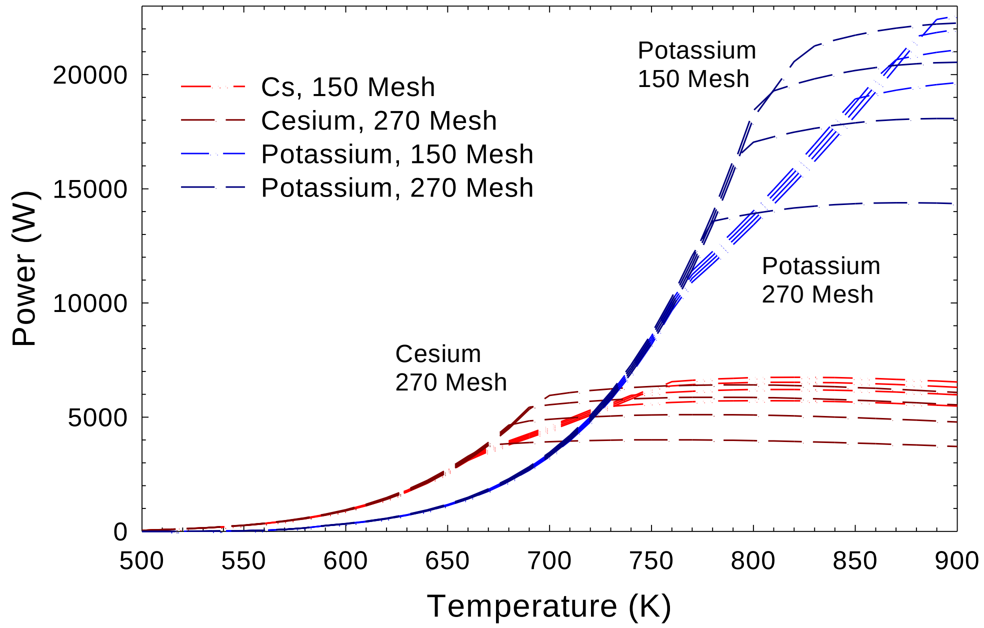


Sonic Limit

- Sonic Limit Occurs when the flow is choked (reaches Mach 1) at the end of the evaporator
  - Occurs in the lower end of the temperature range: low vapor densities mean high vapor velocities to carry a given power
  - Typically seen in alkali metal heat pipes during start-up
  - Rule of thumb: operate with a power less than half the sonic limit.

$$m_{Dot\_Sonic} := \frac{\rho_V \cdot V_{Sound\_V} \cdot A_{Vapor}}{\sqrt{2 \cdot (1+\gamma)}}$$

$$q_{Sonic} = m_{Dot\_Sonic} \cdot \lambda_{fg}$$



Experimental Boiling Limit

- Boiling Limit
  - During normal heat pipe operation, the liquid vaporizes from the top of the wick
  - At high heat fluxes, boiling can occur in the wick
  - Boiling limit occurs when vapor generation interferes with liquid return
- Rules of Thumb for the Boiling Limit
  - Sintered Wicks with Water: ~ 75 W/cm^2
  - Specialized Vapor Chamber Wicks: ~ 750 W/cm^2
  - Screen Wicks with Water: ~ 75 W/cm^2
  - Grooved, Aluminum Wicks with Ammonia: ~ 15 W/cm^2
  - Hybrid Sintered Grooved CCHPs: : ~ 50 W/cm^2

Heat Pipe Limits Takeaways

- Operating Temperature set by source and sink conditions in a well designed heat pipe
- Heat Pipe is designed to operate below the Heat Pipe Limits
- Capillary and Sonic Limit most often limit power
  - Sonic limit primarily in alkali metal heat pipes
- Spacecraft Capillary Limit usually expressed W-m (discuss later)
  - Use effective length during this calculation
- More information: https://www.1-act.com/resources/heat-pipe-performance/

Heat Pipe Applications

- Spacecraft Thermal Control
- Copper/Water Heat Pipes for Electronics Cooling on ground and on Spacecraft
- High Temperature Heat Pipes
- Thermosyphons

Cubesat

GEO Satellite

General Spacecraft Thermal Considerations

- Ultimate Heat Sink = Radiation (No air)
  - Radiators are more efficient at higher temperatures
  - Must operate a lower temperature than your max electronics temperature
  - Know your max component temperatures and thermal resistance network (path from electronics case to radiator)

- Reliability is key (we cannot send maintenance crews up to space!)
  - Understand the mission life
  - Avoid moving parts

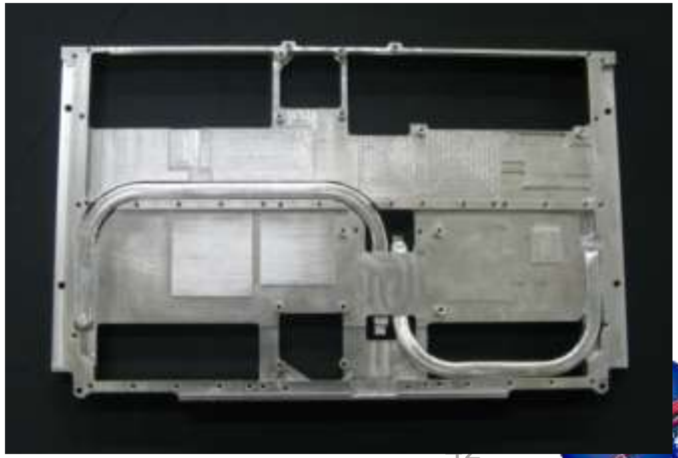
- Low mass and volume are critical

Spacecraft Thermal Control

- Aluminum/ammonia heat pipes accept heat from electronics, transfer the heat to a radiator to reject heat from space
- Radiator has aluminum facesheets, and an aluminum honeycomb
- Heat Pipe panel before and after facesheet close-out (courtesy of Ted Stern of SolAero Technologies Corp.)

Copper/Water Heat Pipes for Electronics Cooling

- Every laptop, and most desktop computers have one or more copper/water heat pipes
- Also used in spacecraft thermal control
- Typical Electronics Cooling Applications
  - Power Electronics
  - Embedded Computers
  - LEDs
  - Lasers
  - Card Chassis: ATR, VME, VPX, etc.
  - RF Amplifiers
  - Heat Sink Optimization
  - Portable Electronics
  - Transmitter/Receiver Modules



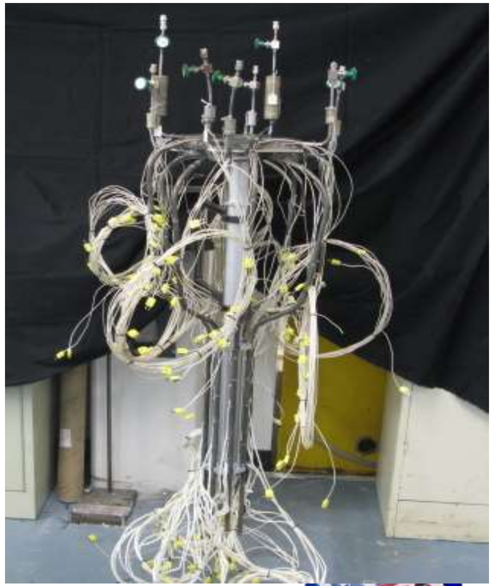
Cu/H_2O Heat Pipes for Spacecraft Thermal Control

- Complement the Al/NH_3 CCHPs
- Wick better against gravity – Ease in Ground Testing
- Provide cooling at board/chip level

	Al-NH_3	Cu-H_20
Power	100's W	10's W
Length	1-3+ m	25+ cm (12+ in.)
Adverse Height	2.5 cm (0.1 in.)	25 cm (10 in.)
Operating Range	-50 to 60 °C	20 to 110+ °C
Diameters/Thickness	0.635 to 2.54 cm (0.25 to 1 in.)	0.4 cm to 0.95 cm (0.16 to 0.375 in.)
Location	Bus	Board
TRL	9	9
Cost	$$$	$ to $$

High Temperature Heat Pipes - Nuclear

- Current Radioisotope Power Systems (RPSs) operate below 500 We.
  - Limited supply of plutonium
- NASA Glenn currently developing the Kilopower system for power generation from 1 to 10 kWe.
  - Space science missions and Martian surface power applications
- Alkali metal heat pipes transfer heat from the reactor to the Stirling convertors
- Water heat pipes transfer the waste heat from the convertors to a radiator panel



Thermosyphon Applications

- Alaska pipeline
  - First large scale application of heat pipes
  - Ammonia/steel thermosyphons
  - Remove heat from ground during winter, to keep the permafrost from melting due to the warm oil flow
- Examined for highway deicing by Walter Bienert
- Sometimes CCHPs are thermosyphons during ground testing (thermal-vac testing)

https://commons.wikimedia.org/wiki/File:Alaska_Pipeline_Closeup_Underneath.jpg © Derek Ramsey, derekramsey.com Used with permission

Heat Pipe Applications Takeaways

- Copper-Water Heat Pipes – Electronics Cooling: Ground and Space
- Grooved Aluminum Heat Pipes – Spacecraft Thermal Control
- Alkali Metal Heat Pipes – Calibration and Space Nuclear Fission
- Thermosyphons – Geothermal, some Thermal-Vac Tests
- This presentation has discussed heat pipe applications with a broad brush. We have not discussed spacecraft applications in detail, since this was already covered in Dr. Jentung Ku's excellent Heat Pipe Tutorial at TFAWS 2015: https://tfaws.nasa.gov/files/TFAWS2015-SC-Heat-Pipes.pdf

Different Types of Heat Pipes

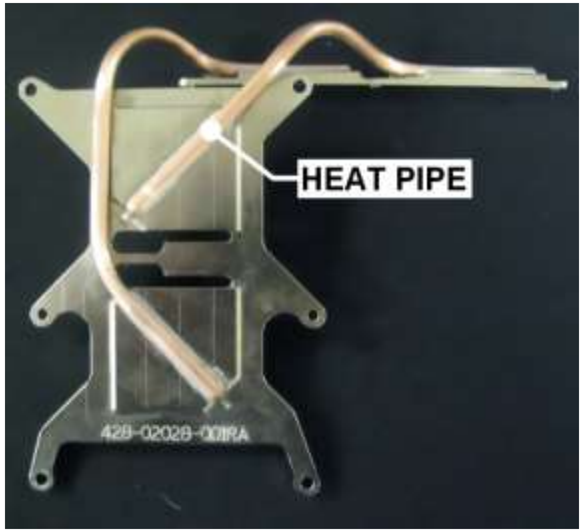
- Constant Conductance Heat Pipes
  - Heat Pipes
  - Hi-K Plates
  - Vapor Chambers
  - Thermosyphons
- Gas-Loaded Heat Pipes
  - Variable Conductance Heat Pipes (VCHPs)
  - Pressure Controlled Heat Pipes (PCHPs)
  - Gas Trap Diode Heat Pipes
- Interrupted Wick
  - Liquid Trap Diode Heat Pipes

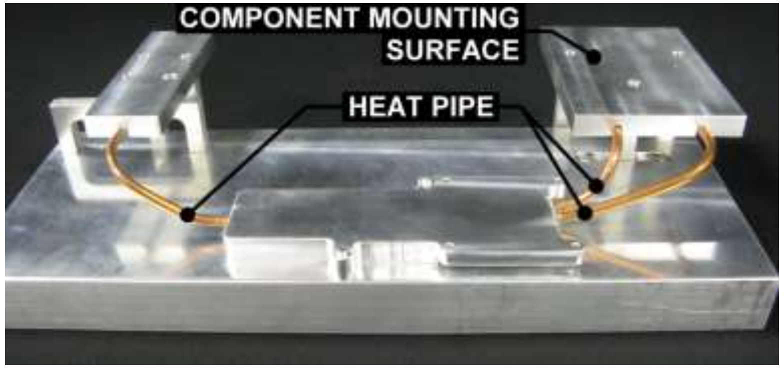
Constant Conductance Heat Pipes

- > 99.99+% of the heat pipes produced by ACT and other companies are Constant Conductance Heat Pipes (CCHPs)
- Working fluid exists at saturation within the heat pipe
  - No other species is present in appreciable amounts
    - Prior to filling, heat pipe is brought under vacuum
  - Can operate over entire liquid-vapor temperature range
  - Internal pressure corresponds to vapor pressure at temperature
  - Envelope is designed to withstand pressure at highest temperature
- Expected operating temperature range determines potential working fluids
- Heat pipe temperature is driven primarily by source/sink conditions
  - Resistances into and out of the heat pipe
  - Water heat pipes do NOT have to operate at 100°C

Spot Cooling Heat Pipe Uses and Benefits

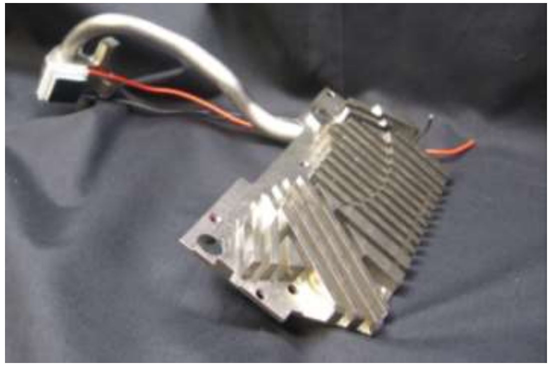
- When to Consider Spot Cooling Heat Pipes
  - Cooling of individual components by transferring heat to an external sink
- Benefits
  - Decrease hot spots to increase maximum power output
  - High Thermal Conductivity
    - 10,000 to 100,000 W/m K
    - Isothermal, Passive
  - Low Cost
    - Only baseline conduction is cheaper
  - Flexibility
    - Can be formed to fit countless geometries
  - Shock/Vibration Tolerant
  - Freeze/Thaw Tolerant

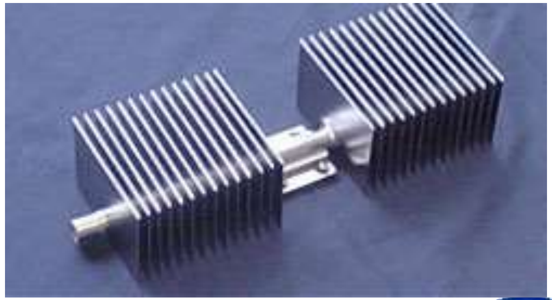




Spot Cooling Heat Pipe Selection Parameters

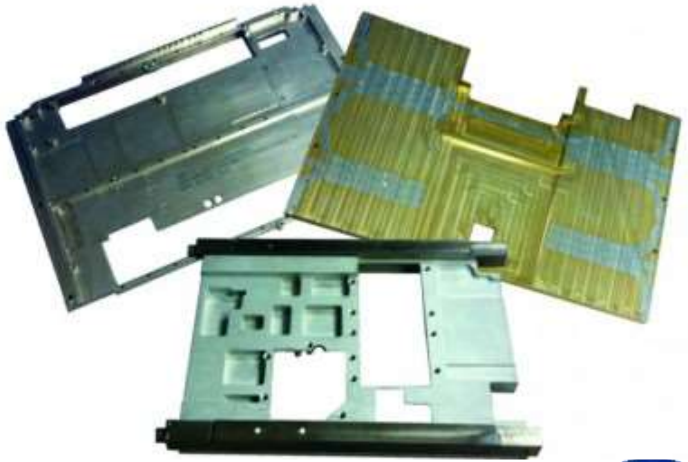
- Not a structural component
- 1-Dimensional Heat Transfer
  - Transports heat from discrete sources
- 9-10 inches (23-25 cm) Max. Height
- Operating temperature ~ 25 to 150°C
  - Higher temperatures with special materials
  - Conduction only below 0°C
- Survival: -55°C to +200°C , depending upon requirements
- Maximum heat flux around 75 W/cm^2
- With proper design, can sustain thousands of freeze/thaw operations





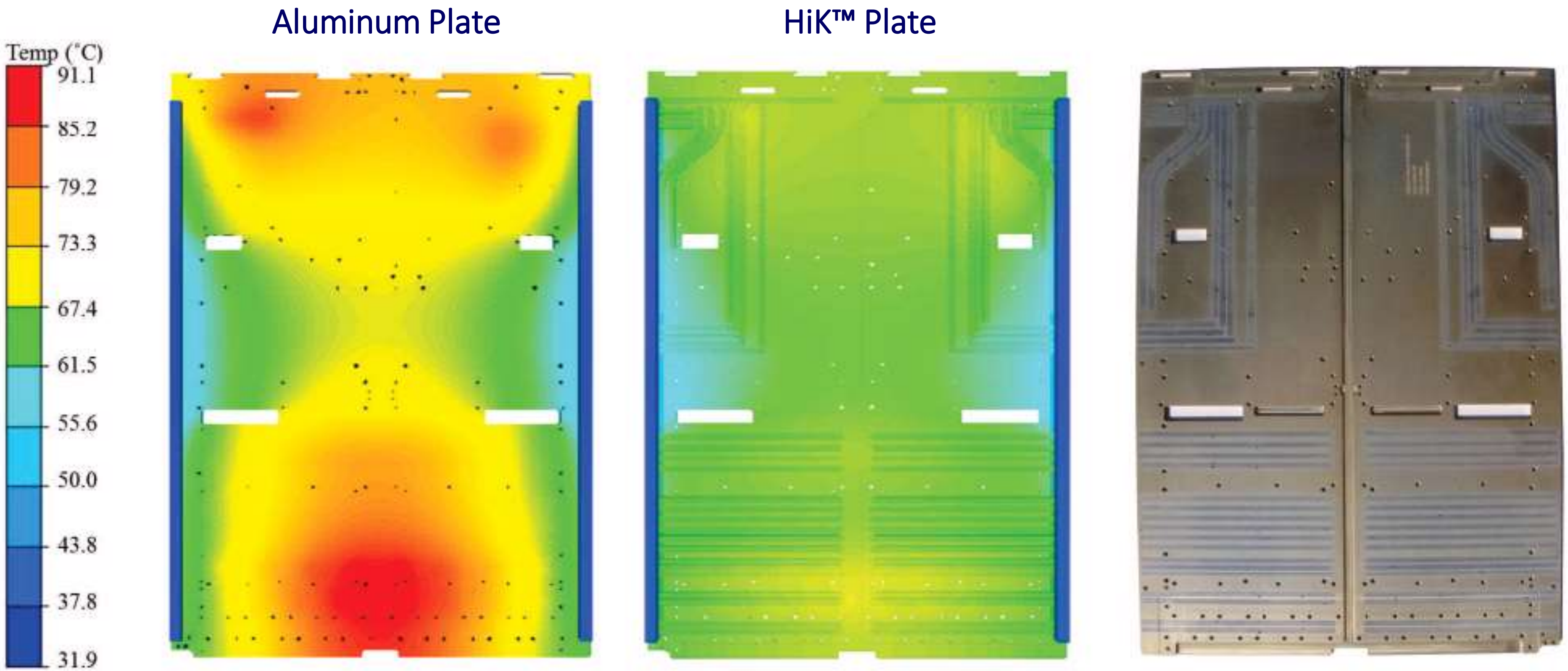
High Conductivity (HiK™) Plates Use & Benefits

- Aluminum Conduction Plates with Embedded Heat Pipes
- Typical Thermal Conductivity: 600-1,200 W/m-K
  - Up to double the k of enhanced conduction cooling
- Reduce Hot Spot Temperatures
- Enhanced Conduction Cooled Cold Plates
  - For Liquid or Air Cooled Chassis
  - Create Higher Fin Efficiency and lower fin weight
- Plate Thickness from 0.072” (1.83mm)
- Structural Strength ≈ Aluminum
- Weight ≈ 1.1 to 1.2 of Aluminum



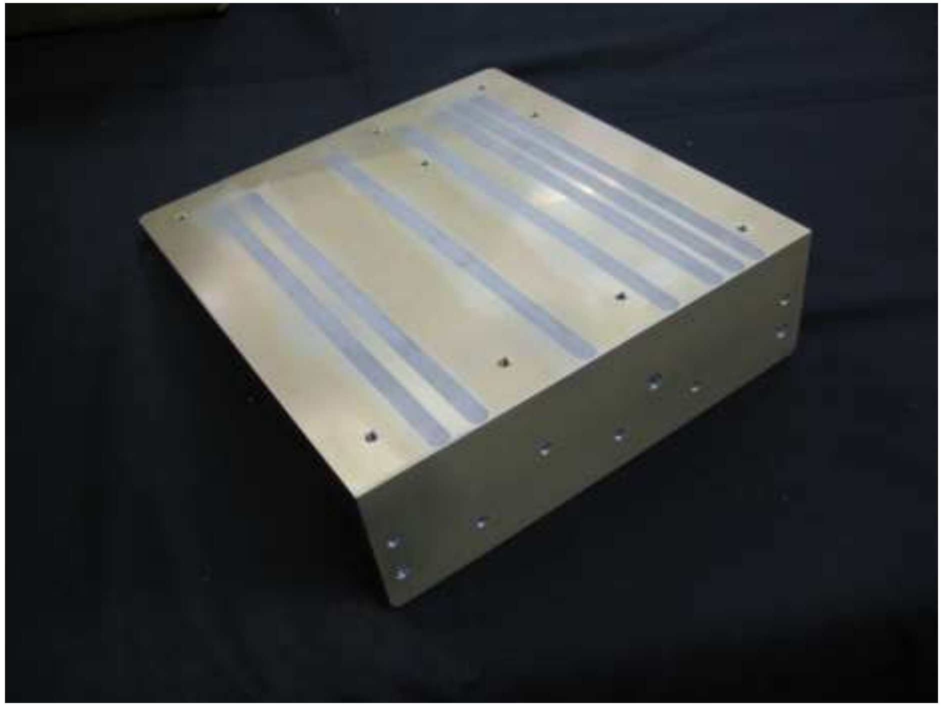
HiK™ Plate Isothermalization

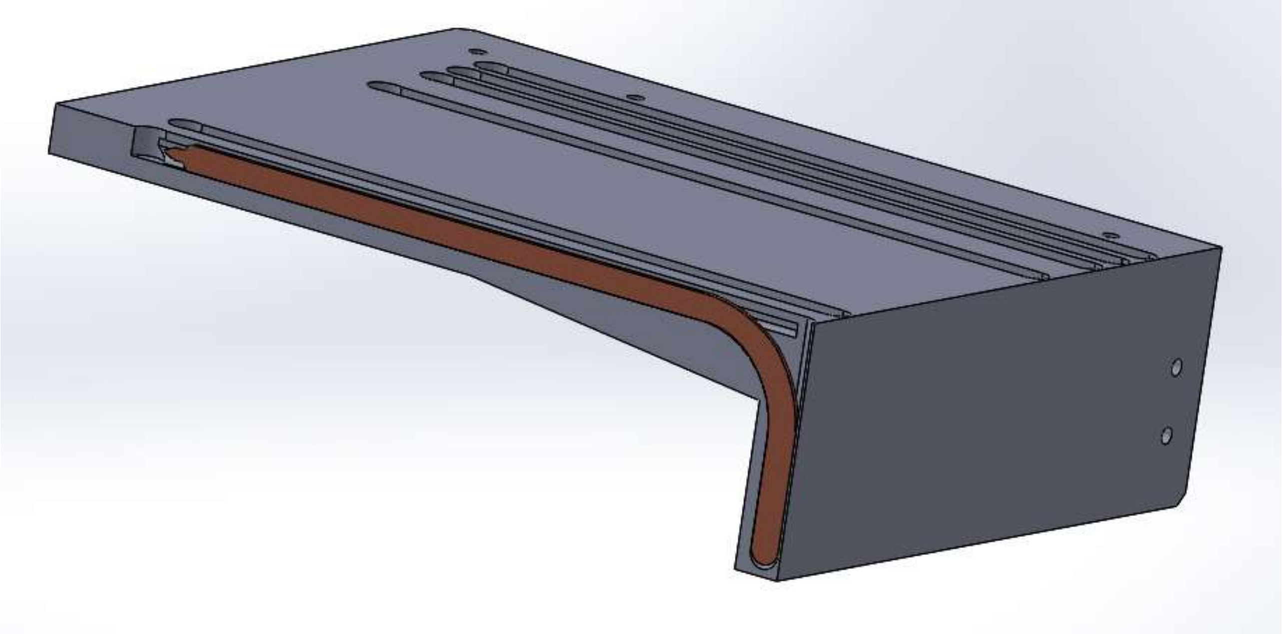
- Identical Dimensions, 22°C Reduction in Peak Temperature Measured



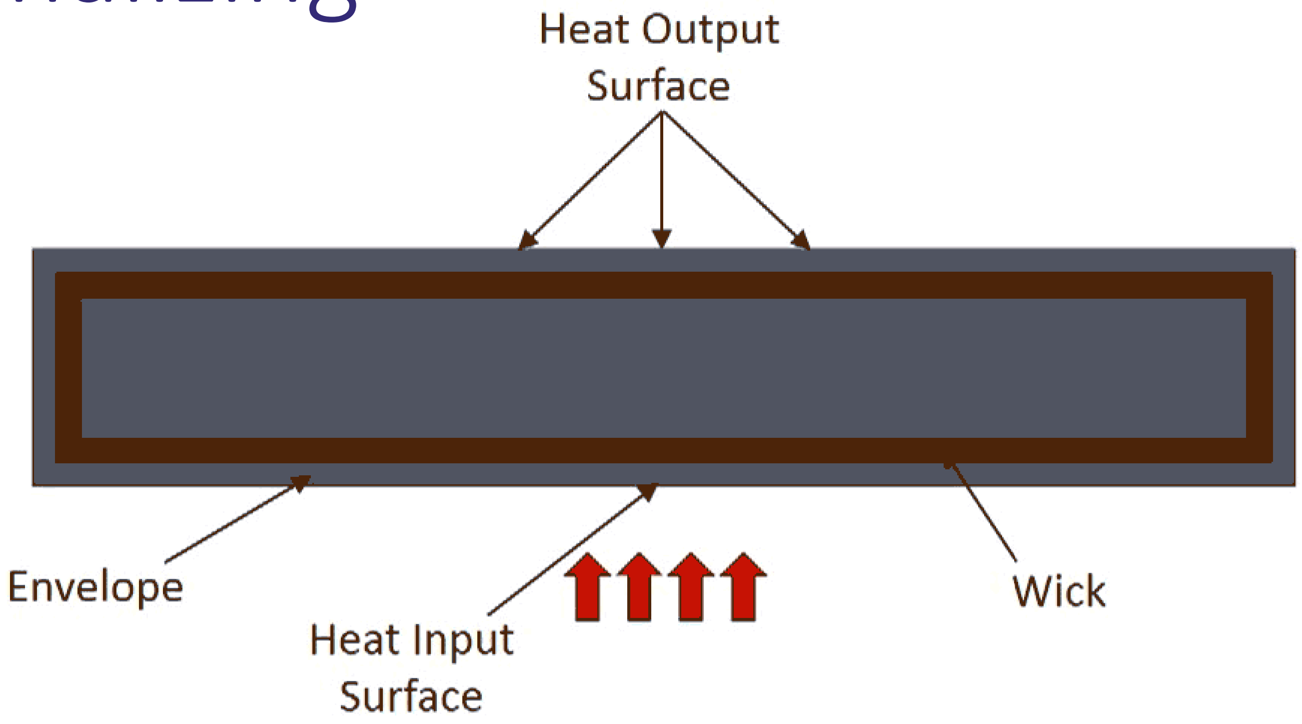
HiK™ Plates can Bend Around Corners

- Also can bend heat pipes to transfer heat around corners





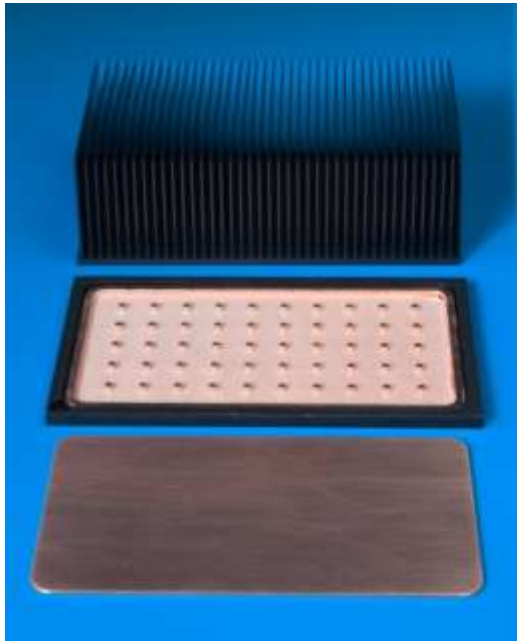
Vapor Chambers – Heat Spreading and Isothermalizing



- Roughly 2.3 times the density of a HiK plate, but an increase in thermal conductivity of 10 to 100 times
- https://www.1-act.com/resources/heat-pipe-fundamentals/different-types-of-heat-pipes/vapor-chambers/

Vapor Chamber Use and Benefits

- Benefits
  - Multi-component mounting
  - Thickness from 0.12” (3 mm)
  - Excellent Heat Spreading
    - Resistance < 0.15 °C/W, < 0.08 °C/W for special wicks
  - Excellent Isothermalization
  - High heat flux to low heat flux transformation
  - Ideal for high heat flux/high performance applications
    - Heat flux > 60 W/cm^2, up to 750 W/cm^2 for special wicks



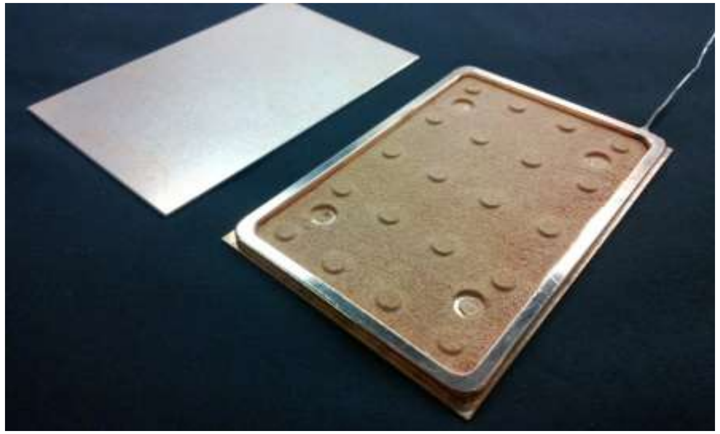
Typical Components

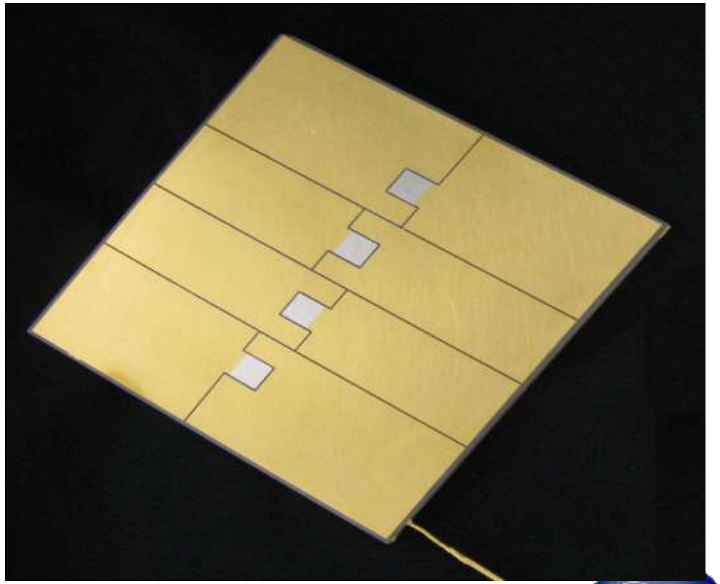
Vapor Chamber Internals

Assembled Vapor Chamber

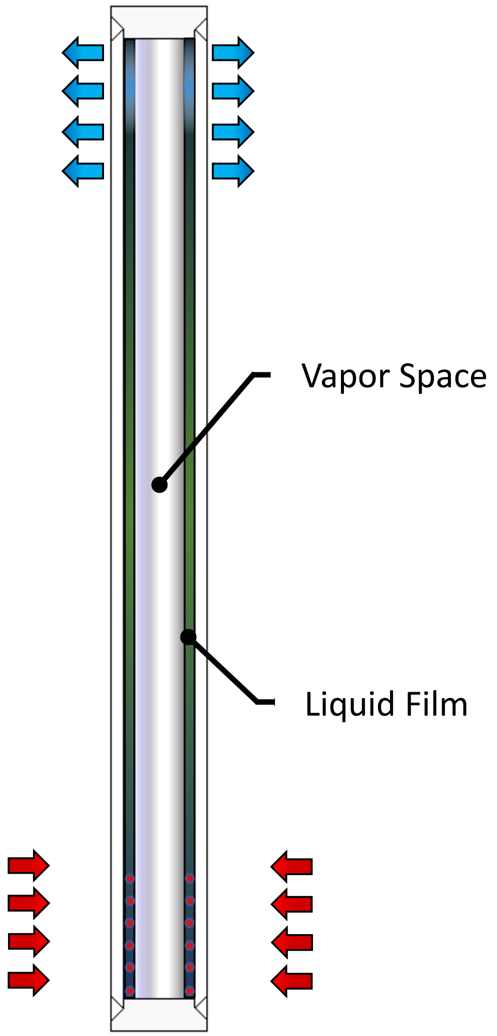
Vapor Chamber Selection Parameters

- Use Vapor Chambers for
  - Very high heat fluxes, up to 1000 W/cm^2
  - Flux transformation in a thin structure
  - Very uniform temperature profiles
- Minimum thickness: 3mm (0.120")
- Maximum Dimensions: 10 in. x 20 in. (25 cm x 50 cm)
- Maximum Heat Flux for standard systems: ~ 60-70 W/cm^2
  - 500 W/cm^2 over 4 cm^2 Optimized Wick, specific location
- Minimum Temperature: -55°C
  - Conduction Heat Transfer only below 0°C
- Maximum Temperature: ~105°C
  - New IP increases to 150°C
- Envelope Materials: Copper, AlN Direct Bond Copper for direct mounting of electronics





Thermosyphon Operation Summary



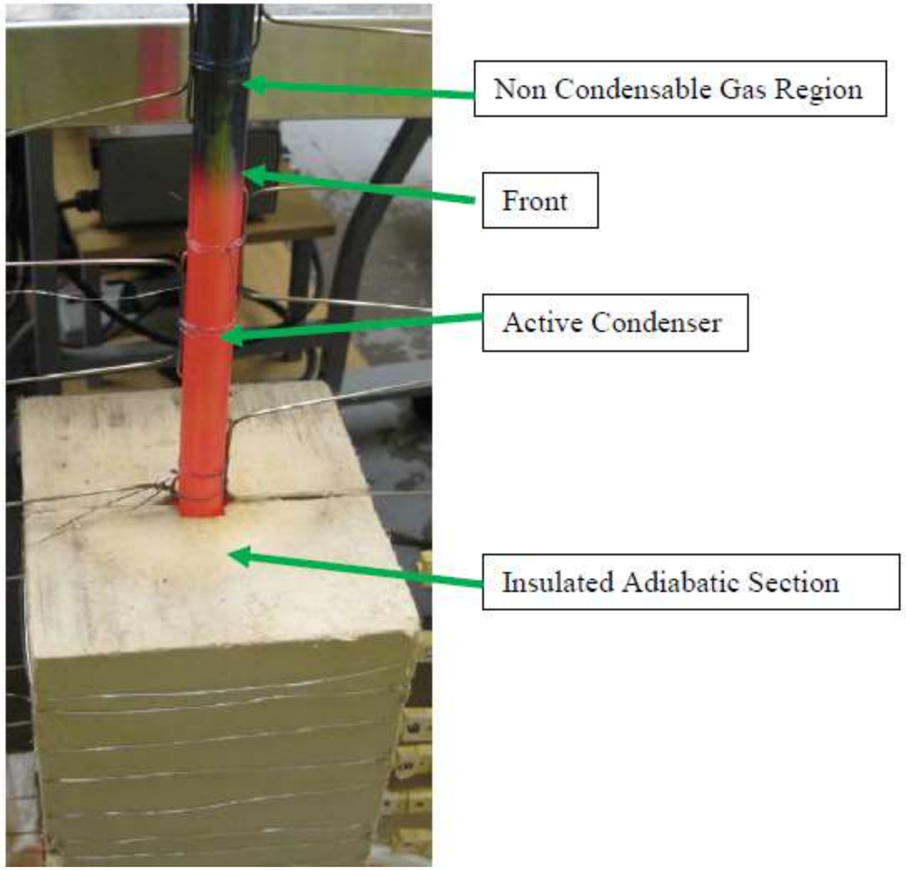
- Normal Heat Pipes can operate in any orientation
  - Use capillary forces in the wick to return liquid to the evaporator when the evaporator is elevated above the condenser
- Thermosyphons are gravity-aided heat pipes
  - Evaporator must be located below the condenser
  - Fluid returns to the evaporator by gravity
  - Evaporator normally wicked for start-up
- Higher powers
- Essentially unlimited lengths
- CCHPs sometimes operate as thermosyphons during Thermal-Vac testing

Differences between Heat Pipes and Thermosyphons

Parameter	Heat Pipe	Thermosyphon
Passive	Yes	Yes
Superconductor	Yes	Yes
Two-Phase	Yes	Yes
Vacuum Tight	Yes	Yes
Wick	Everywhere	Evaporator Only
Liquid Returns by	Capillary Wick	Gravity
Orientation	Any	Evaporator Lower than Condenser
Limit	Capillary	Flooding

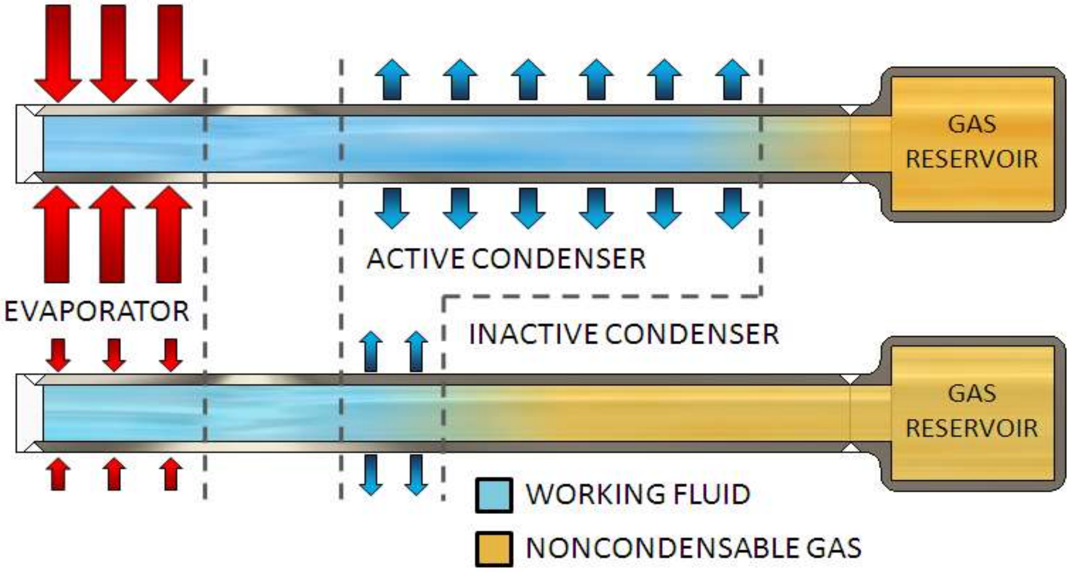
Gas-Charged Heat Pipes

- Standard heat pipes are evacuated, then filled with the working fluid
  - Vapor space contains only working fluid vapor
- In Gas Charged Heat Pipes, a Non-Condensable Gas (NCG) is added
  - Noble Gas
  - Typically argon for horizontal heat pipes and microgravity, helium for vertical
- NCG is driven to the end of the pipe
- VCHPs, PCHPs, Gas-Charged Diodes



Variable Conductance Heat Pipe (VCHP) Operation

- During operation, the working fluid drives the Non-Condensable Gas (NCG) to the condenser
- The portion of the condenser blocked by NCG is not available for heat transfer by condensation
  - Inactive condenser region
- Remaining condenser is available for heat transfer
  - Active condenser region
- Active and inactive length depend on working fluid pressure



VCHP Applications

- Maintain constant evaporator temperature over varying power and sink temperatures
  - Standard aerospace application
- Dual condensers for radioisotope Stirling applications
  - Radioisotope heat must always be removed
  - Dump heat to secondary condenser when Stirling is turned off
- Variable Thermal Links – Discussed Later
- Aid in Start-up and Shut-down from a frozen state
  - Prevents sublimation in water pipes when frozen
- Dual Condensers, Variable Thermal Links and Frozen Startup:
  - https://www.1-act.com/resources/heat-pipe-fundamentals/different-types-of-heat-pipes/variable-conductance-heat-pipes-vchps/

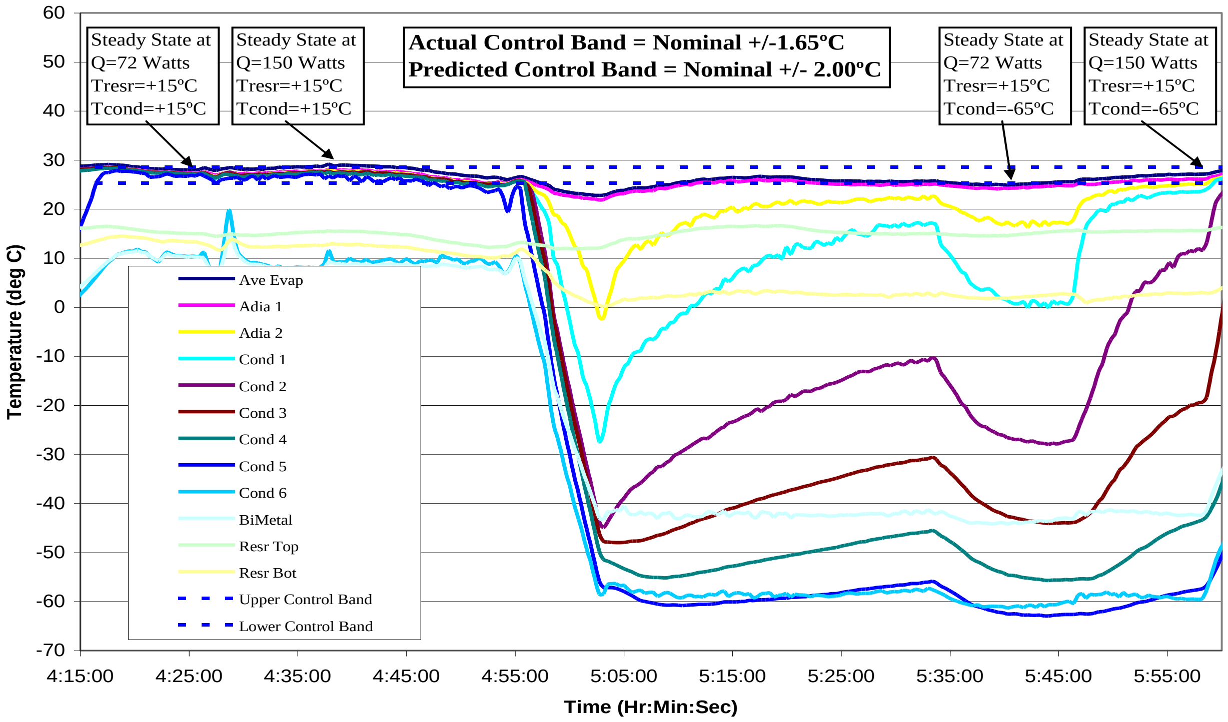
Variable Conductance Heat Pipes

- VCHPs are most often used for temperature control in spacecraft applications

- Standard VCHP has an evaporator, a condenser, and a reservoir for Non-Condensable Gas (NCG)
- Cold-biased reservoir is located next to the condenser.
- Electrical heaters control the reservoir temperature
- Typically maintain evaporator temperature control of ± 1-2 °C over widely varying evaporator powers and heat sink temperatures
- Roughly 1-2 W electrical power required for the reservoir heaters

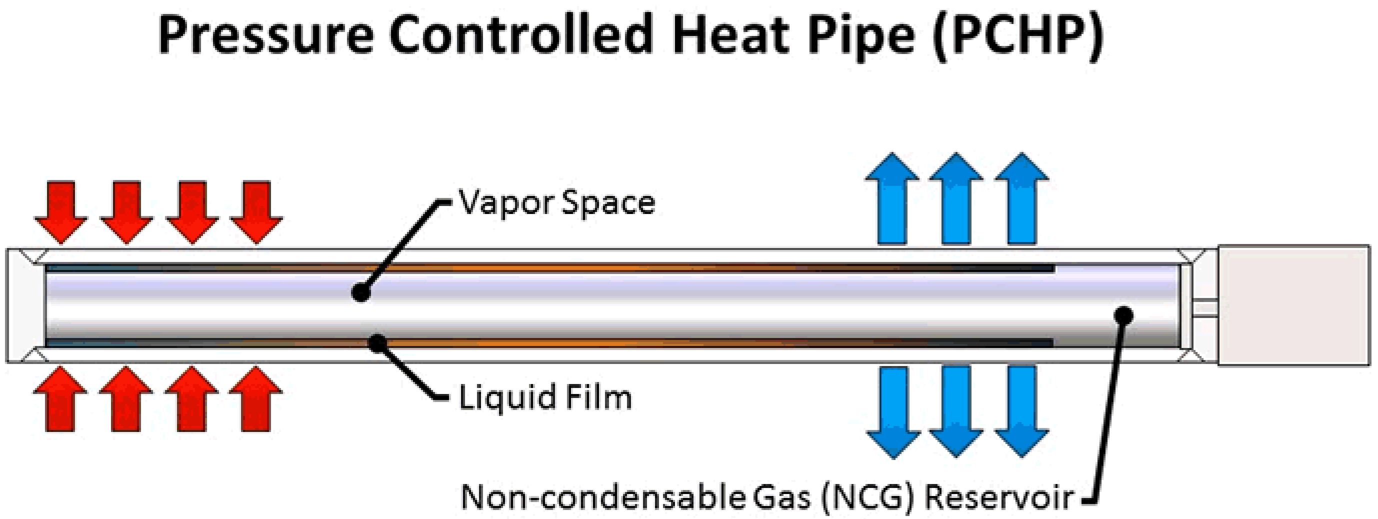
Standard VCHPs for Temperature Control

- Aluminum/Ammonia Design
- Evaporator controlled to ±1.65ºC
  - Input power was varied from 72 Watts to 150 Watts
  - Sink temperature ranged from +15ºC to -65ºC
  - Reservoir Thermostatically Controlled at 15°C

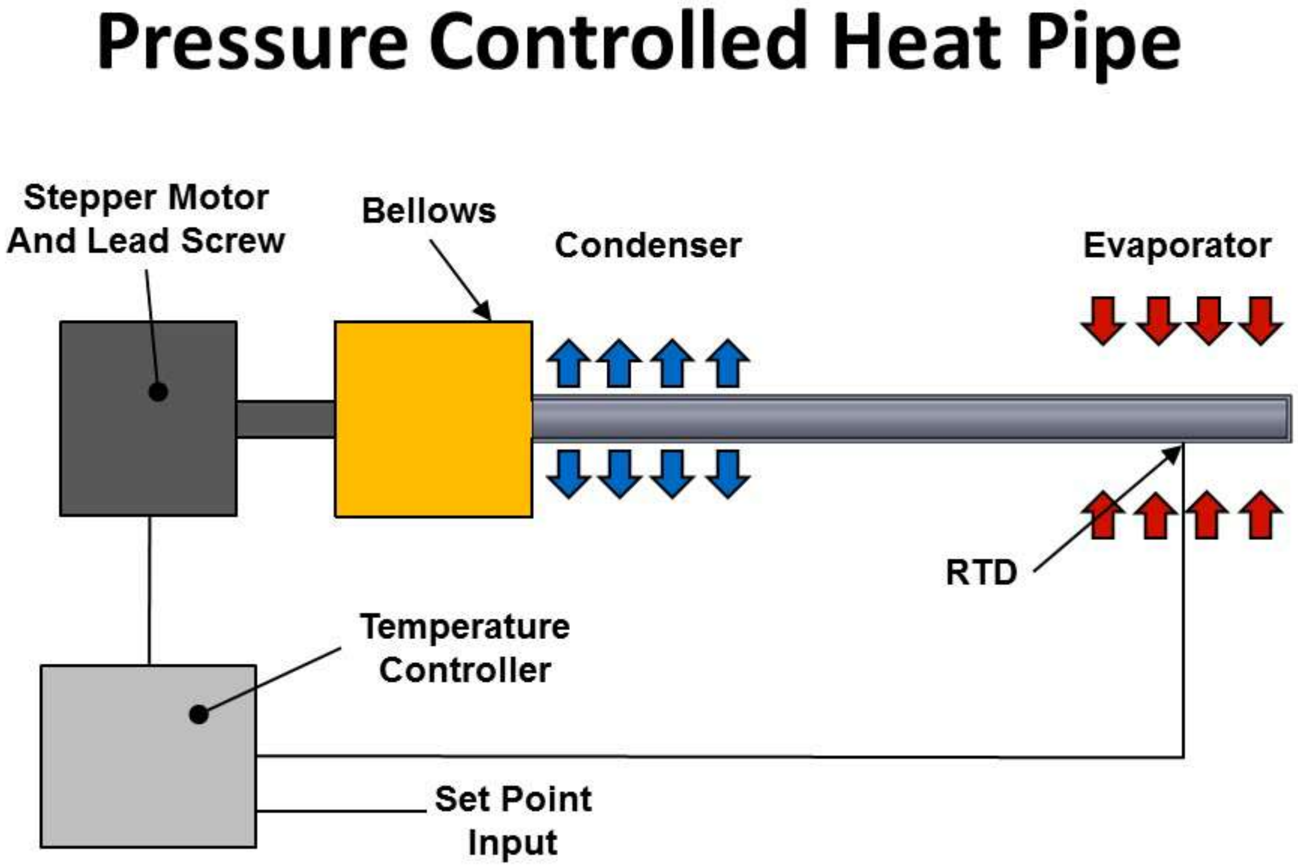


Pressure Controlled Heat Pipe (PCHP)

- Heat pipe pressure and temperature set by vapor pressure of working fluid.
  - Reservoir is linked to the vapor space so NCG is at the same pressure
- Vary reservoir volume or amount of gas
  - Actuator drives bellows to modulate the reservoir volume
  - Pump/vacuum pump adds/removes gas
- Used for
  - Precise Temperature Control
  - Power Switching

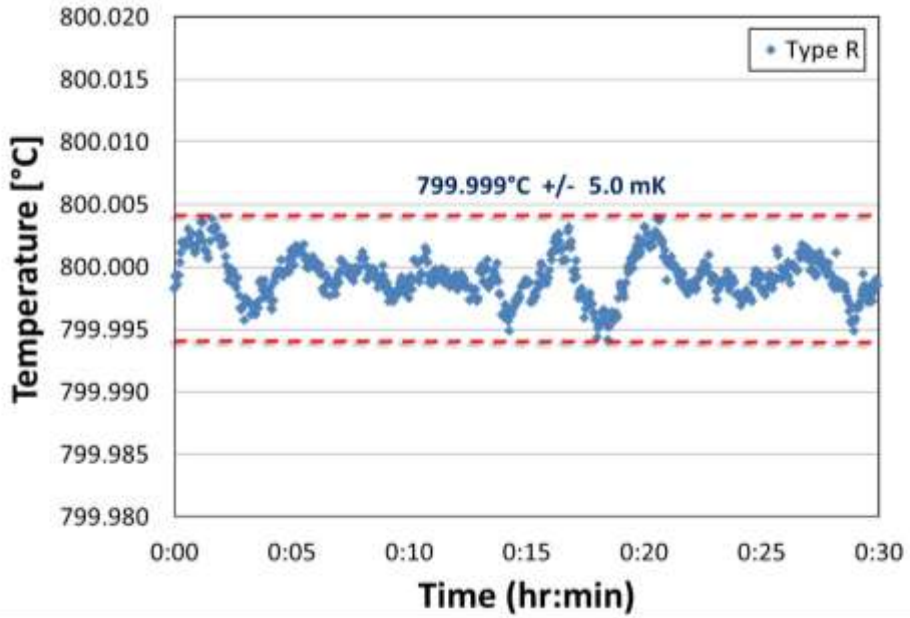


PCHP for Precise Temperature Control



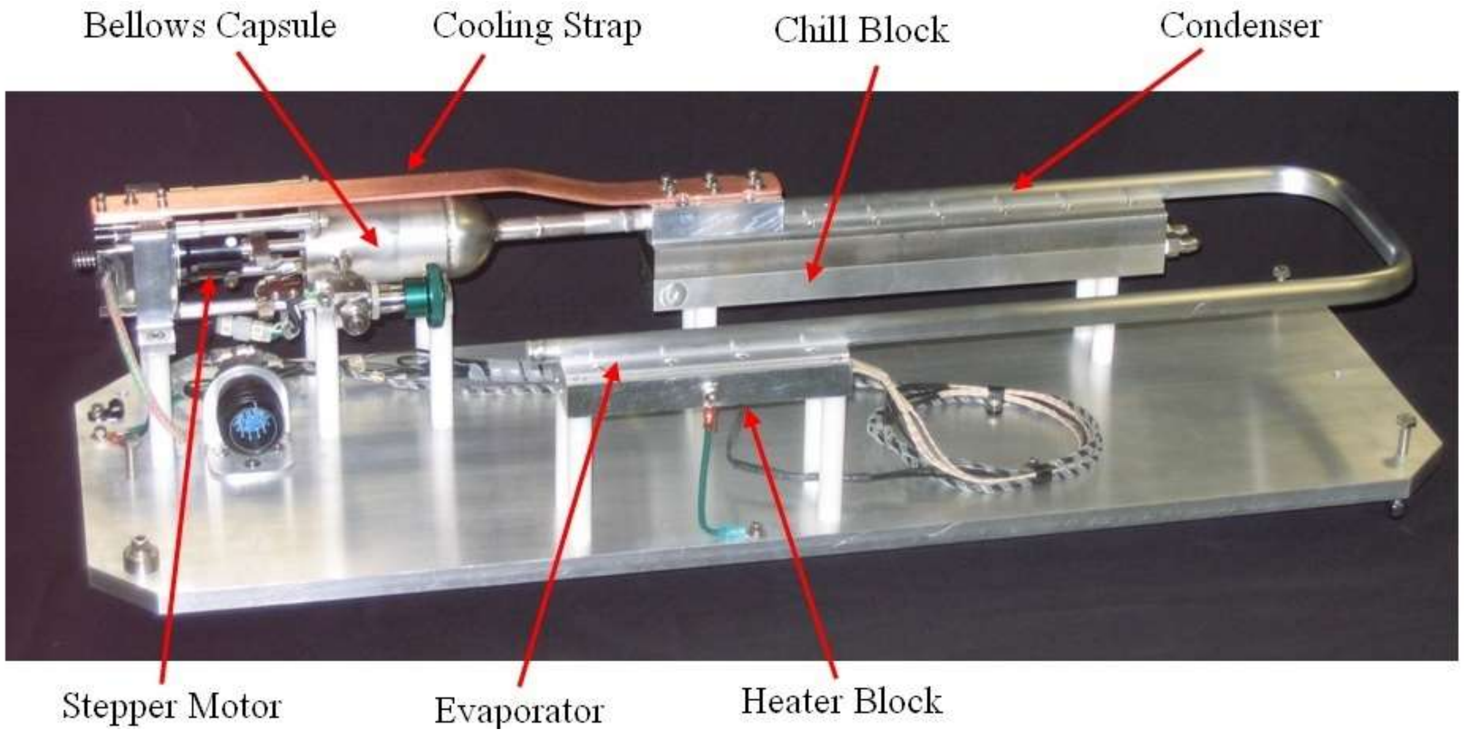
PCHPs for Precise Temperature Control

- Annular heat pipes are often used for calibration of reference temperature sensors
  - Isothermal within milli-Kelvin
- PCHP calibration furnace adds tight temperature control
- ± 5 milli-Kelvin over a period of two hours

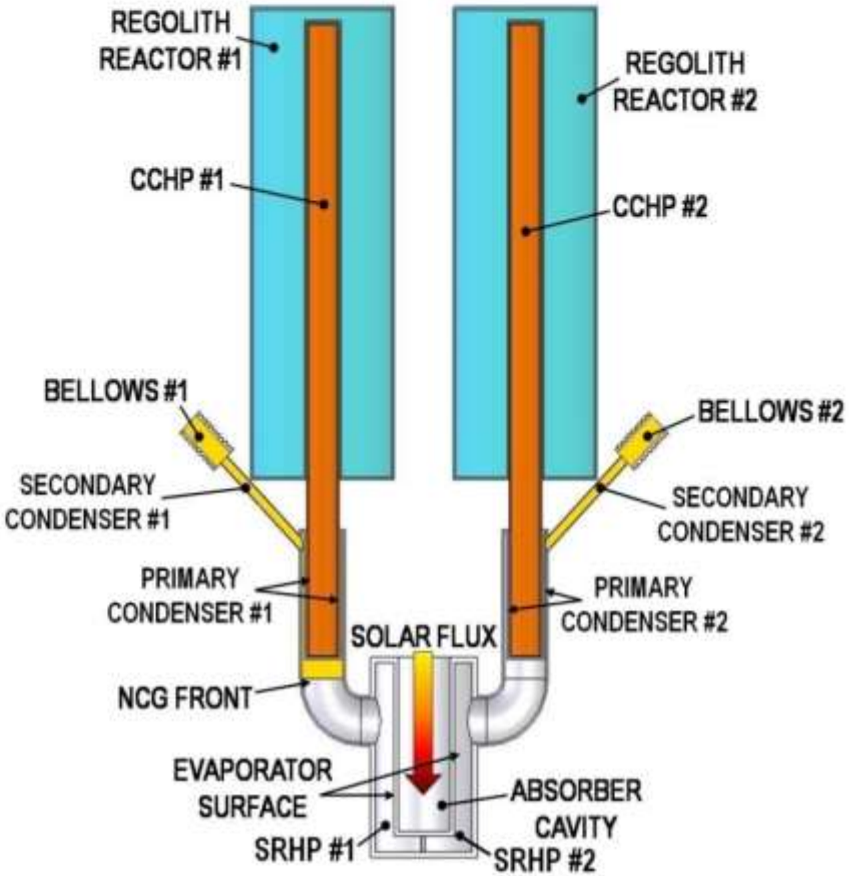


PCHPs for Precise Temperature Control in Space

- Flight-like Aluminum/Ammonia PCHP with stainless bellows
- Control temperature to within 8 mK
  - Adjust for varying power or sink conditions



PCHPs for Power Switching – Lunar Regolith

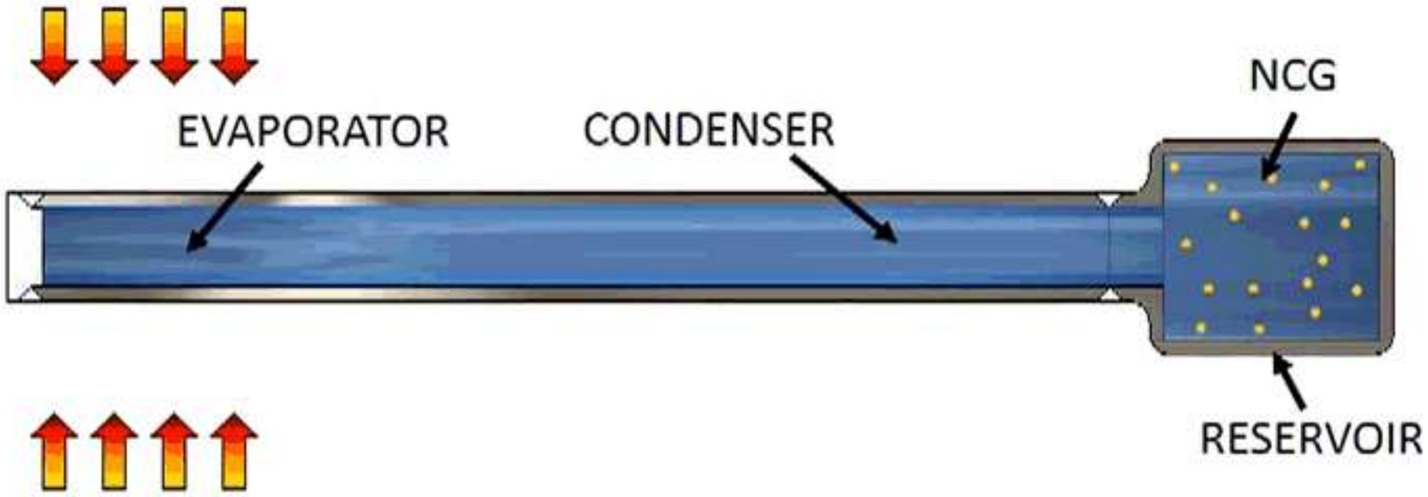


- A single power source (solar concentrator) is used to provide heat to two regolith reactors in order to extract oxygen from lunar regolith
- There are three major stages of processing for each side:
  - RHS (Right Hand Side) Warm Up (constant power)
  - RHS Process (power reduction)/LHS (Left Hand Side) Warm Up (constant power)
  - LHS Process(power reduction)/RHS Warm Up (constant power)
- System utilizes two separate PCHPs equipped with an NCG to regulate the amount of power that goes into each reactor depending on the need
- A secondary condenser is used to dissipate any excess power that is experienced as the NCG front moves closer to the end of the primary condenser

Diode Heat Pipes

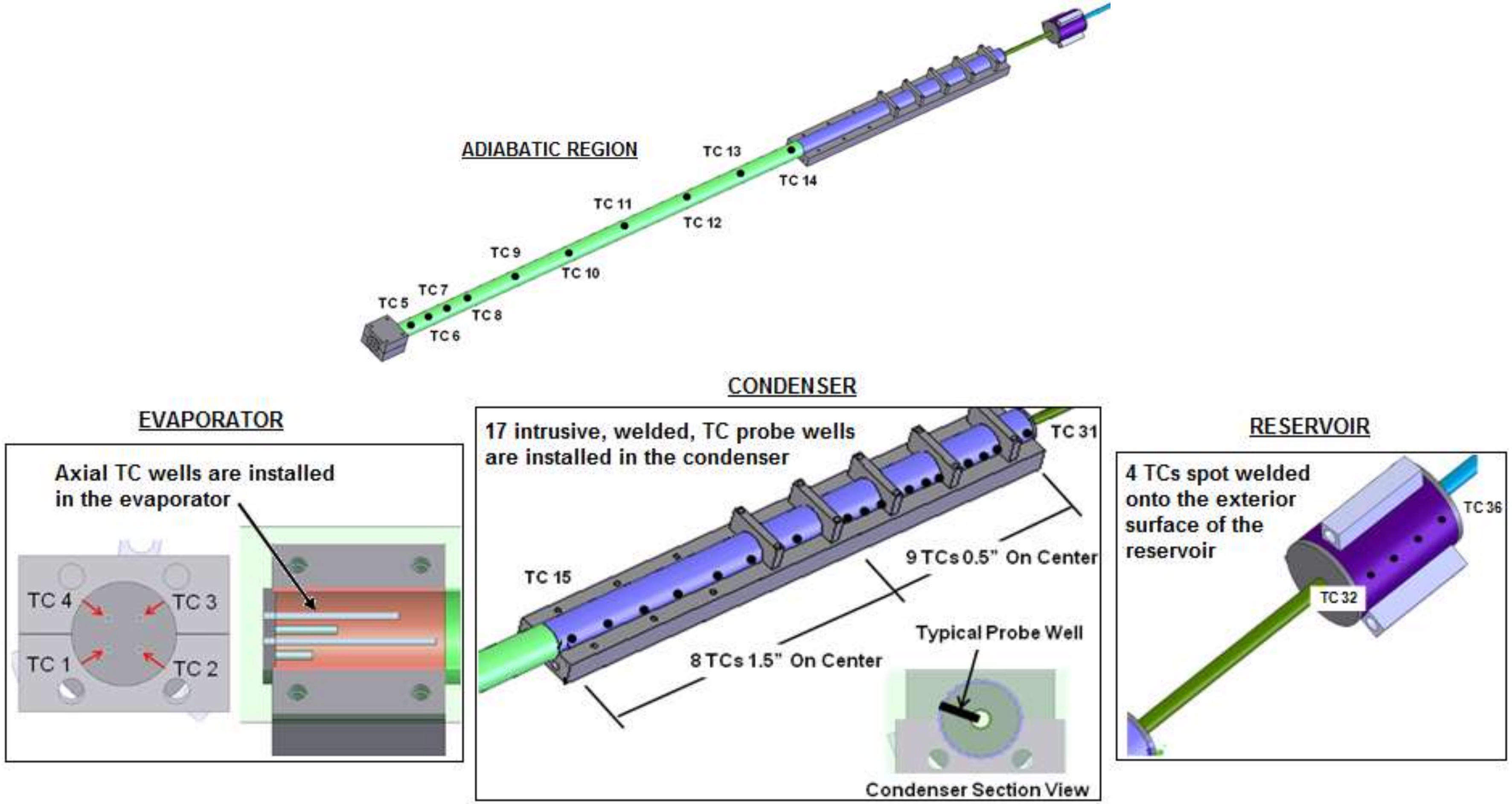
- Diode Heat Pipes designed to act like an electronic diode
- Evaporator Hotter Than Condenser
  - Heat Flows
- Condenser Hotter Than Evaporator
  - Blocks Heat From Flowing
- No method to throttle heat in the forward direction
- VCHPs and LHPs will function as diode if direct sun heats up the evaporator
  - VCHP evaporator blocked by gas
  - Loop Heat Pipe condenser fills with vapor
- Thermosyphon also a diode
  - No liquid available if heat from the top

Gas Diode Heat Pipes



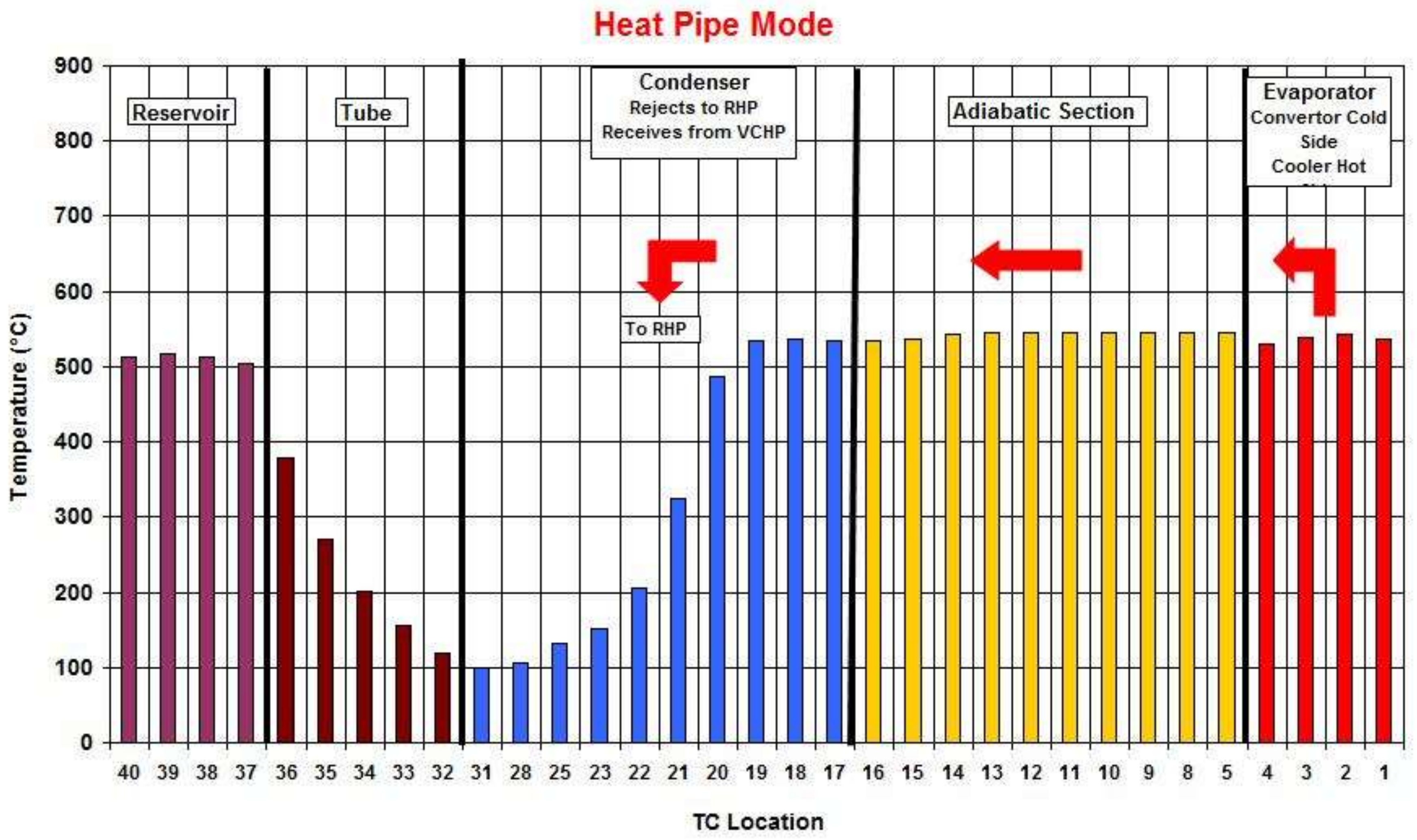
- During normal operation, functions very similar to a VCHP
  - Gas reservoir at condenser end with NCG
  - NCG blocks of parts of the condenser depending on the thermal load
- During reverse operation vapor flows in the opposite direction
  - NCG gas moves to the opposite end of the heat pipe due to the change in pressure
  - NCG gas blocks off what would be the condensing end, effectively “shutting off” the HP

Gas-Trap Diode Heat Pipe Design

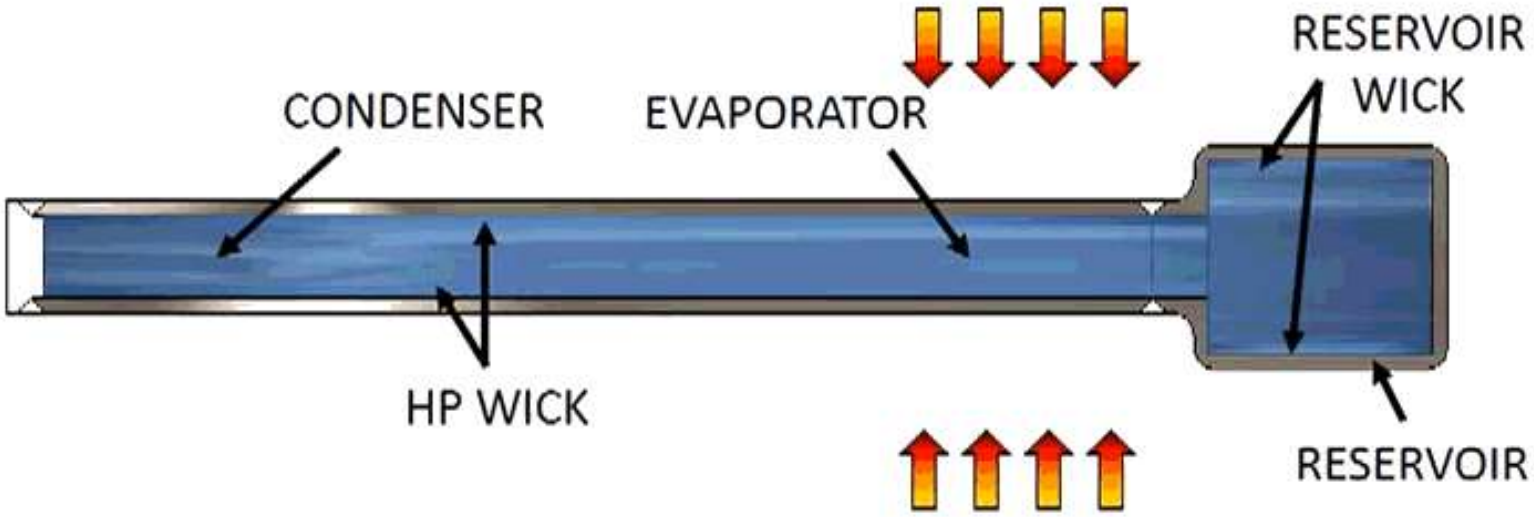


C. Tarau et al., "Diode Heat Pipes for Venus Landers," 9th IECEC, San Diego, CA, July 31 - August 3, 2012.

Gas Diode Heat Pipe Development



Liquid Trap Diode Heat Pipes



- Wicked reservoir located at evaporator end of HP
  - Reservoir wick does not communicate with HP wick
- In normal operation functions like CCHP
  - Liquid evaporates at hot end, condenses at cold end and returns to hot end via HP wick
- In reverse direction, liquid evaporates at the hot side and condenses in the reservoir and becomes trapped
  - Separate reservoir and heat pipe wicks trap the condensate in the reservoir, preventing it from returning to the hot end, effectively "shutting off" the HP

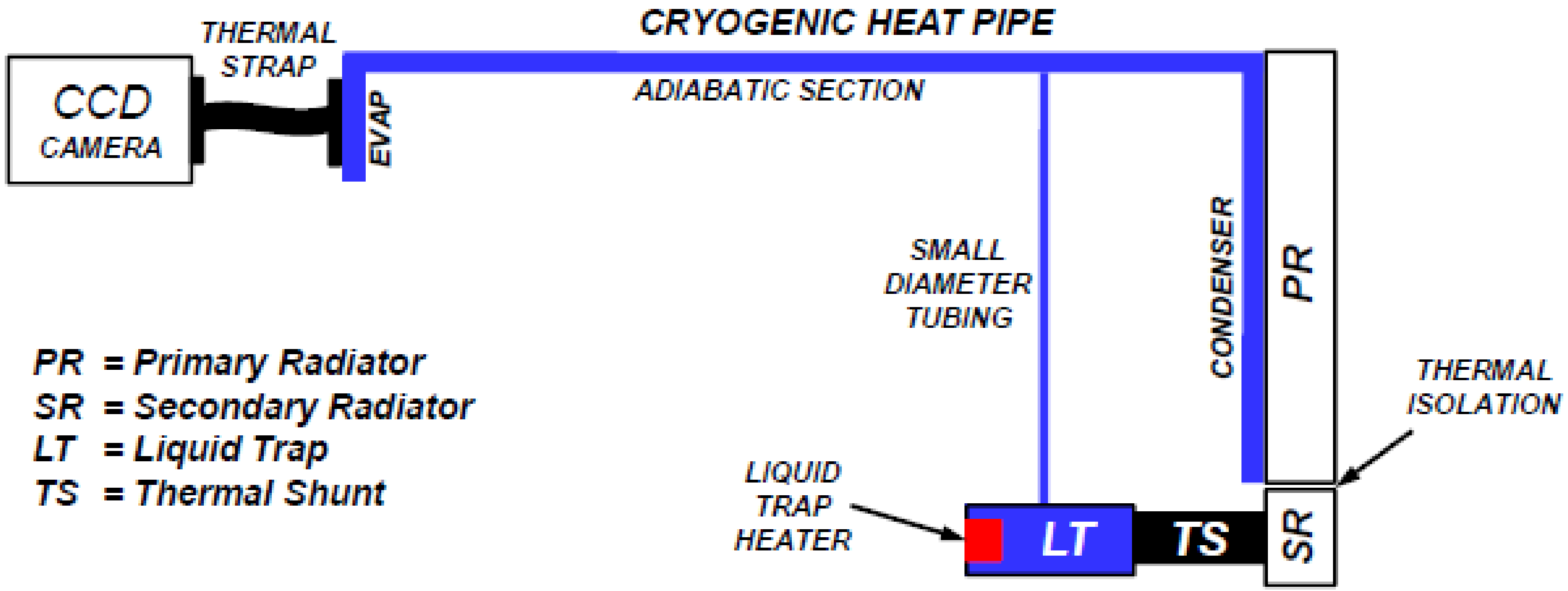
Liquid Trap Diode Example

- Liquid trap diode developed by David Bugby to link cameras to a cryoradiator
- During normal operation, a heat pipe cools the cameras, transferring heat to the cryoradiator at 140 K
- Periodically, the Lenses must be decontaminated by heating them up
  - Hot-side decontamination temperature: 293 K
  - Need to minimize the hot-side decontamination heater power
  - Need to turn off the heat pipe
- Solution: Cryogenic heat pipe with thermal switching capability provided by a secondary radiator thermally isolated from the primary radiator, a thermally shunted liquid trap, and small liquid trap heater.

- D. Bugby et al., "Cryogenic Heat Pipe Thermal Transport and Switching System," 2010 Spacecraft Thermal Control Workshop"

Liquid Trap Diode

- During normal operation, the small liquid trap heater keeps the liquid trap warm enough so that it is filled with vapor only so the heat pipe is ON.
- During decontamination, the liquid trap heater is turned off and all the working fluid migrates to the liquid trap turning the heat pipe OFF.

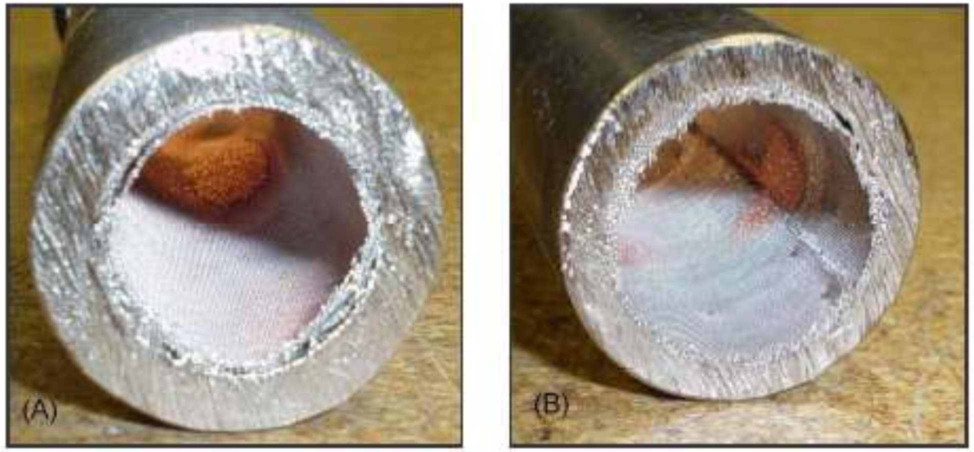


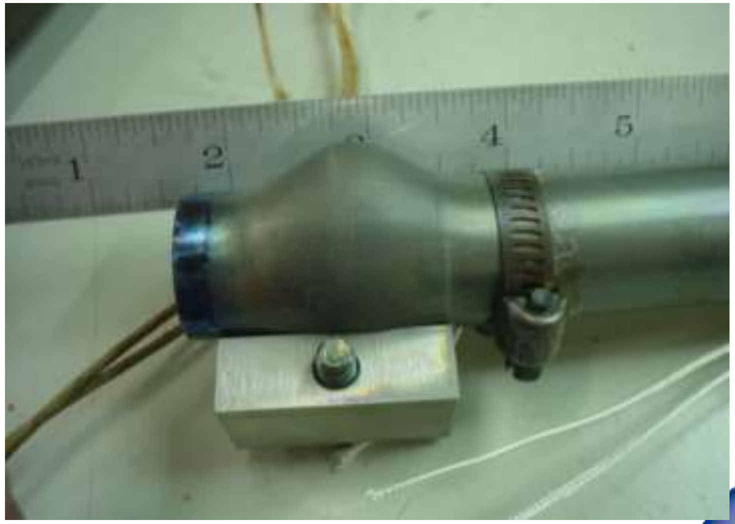
Different Types of Heat Pipes – Takeaways

- Standard heat pipes are always on and operate in both directions
- VCHPs can be used for temperature control, as an emergency heat dump, and to passively shut down at low temperatures
- PCHPs are used in precise temperature control, and for high temperature power switching
- Diode Heat Pipes allow heat transfer in one direction, with minimum heat transfer in the other
- Additional Heat Pipe Types: https://www.1-act.com/resources/heat-pipe-fundamentals/different-types-of-heat-pipes/

Heat Pipe Working Fluids and Compatibility

- Envelope/Fluid Compatibility
- Fluid Selection
  - Merit Number
- Commonly Used Fluids
- Operating Temperature Range
- Life Tests to Determine Compatible Systems
  - Compatible and Incompatible Material Systems
- Most Commonly Used Fluid/Envelope Pairs
- Covered Later
  - Life Tests for Process Verification
  - NCG Generation Testing





Envelope/Wick/Fluid Compatibility

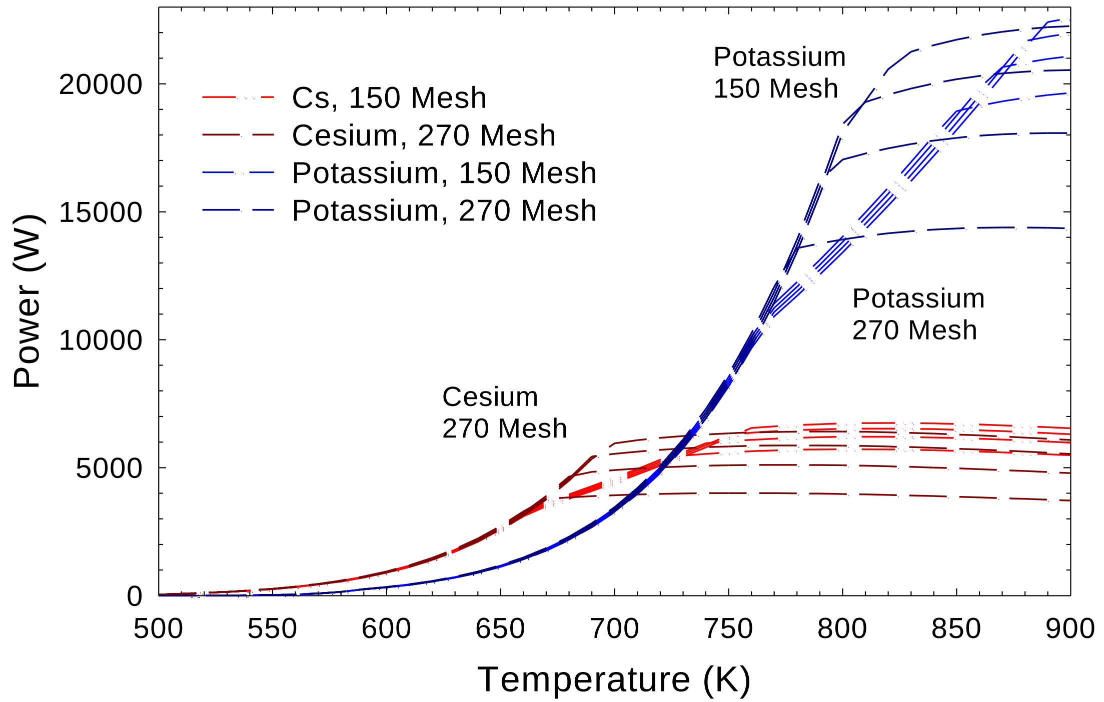
- The wall and wick must be completely compatible chemically with the working fluid
  - No wick dissolved by (or chemical reaction with) the working fluid
  - It takes extensive life testing to assure compatibility.
  - There’s nothing worse in this business than a compatibility failure. (Picture a spacecraft that fails in orbit because its heat pipe radiator failed.)
- Problems that can occur
  - Gas Generation (most Common)
  - Corrosion
  - Materials Transport
  - Deformation

Working Fluids – Operating Temperature Ranges

- Theoretically, fluids can be used from just above the freezing point, to just below the critical point
- In practice, fluid range is smaller
- Low Temperature Limit
  - Viscous and Sonic Limits
- High Temperature Limit
  - High Pressures
  - Low Surface Tension
  - Reduced Latent Heat
- Water Theory
  - 0.01°C Triple Point
  - 373.9°C Critical Point
- Water Practice
  - ~10-20 °C lower limit, depends on heat pipe design
  - 300°C short term upper limit to date (vapor pressure, surface tension)

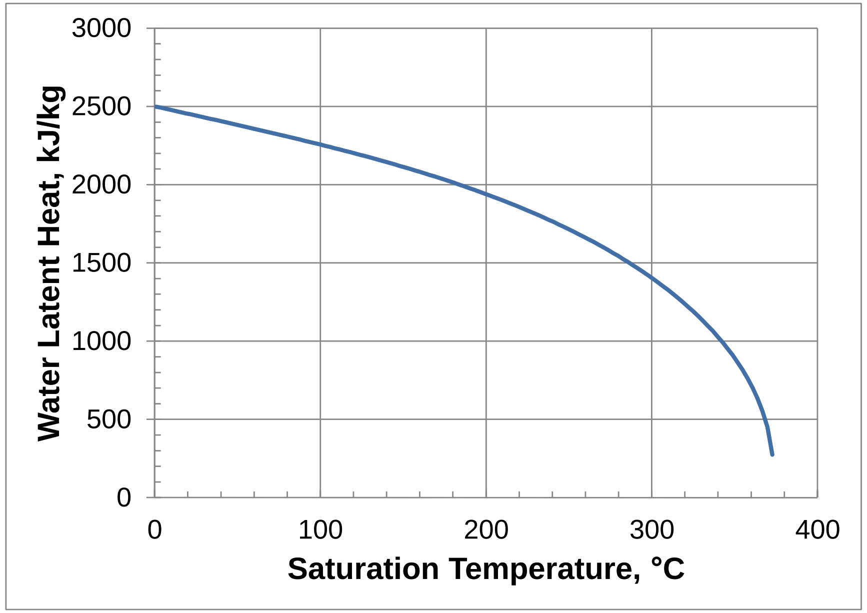
Low Temperature – Sonic Limit

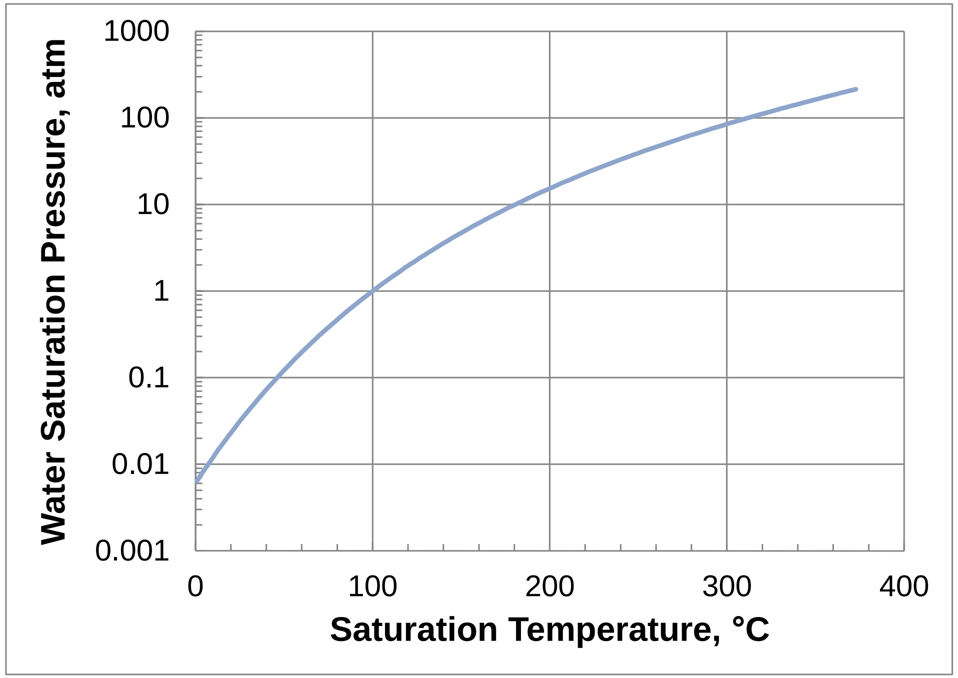
- Cesium and Potassium Heat Pipes
  - Sonic Limit controls at low temperatures
  - Capillary Limit at higher temperatures
- For this specific design, Cs works above ~400°C, K above ~ 500°C

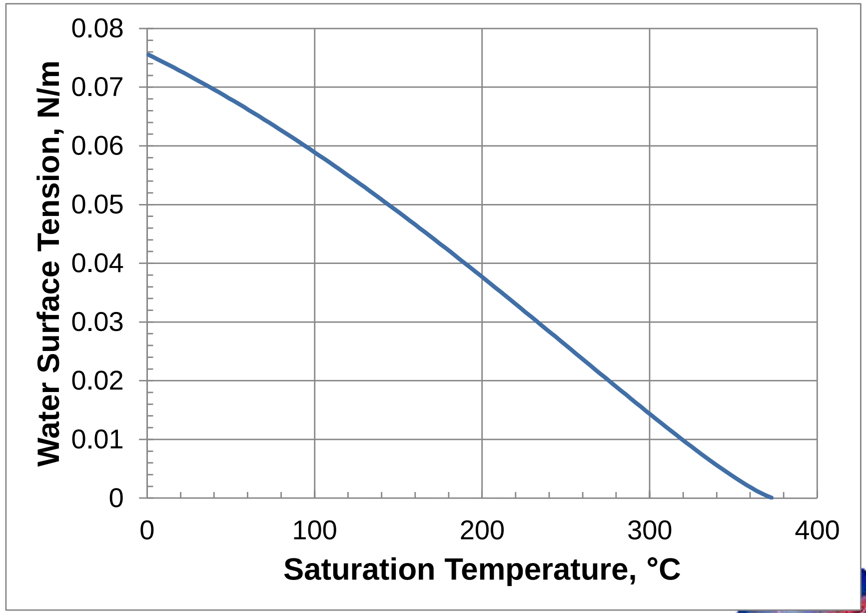


Upper Temperature Limit

- Vapor Pressure gets very high
- Surface Tension and Latent Heat approach zero

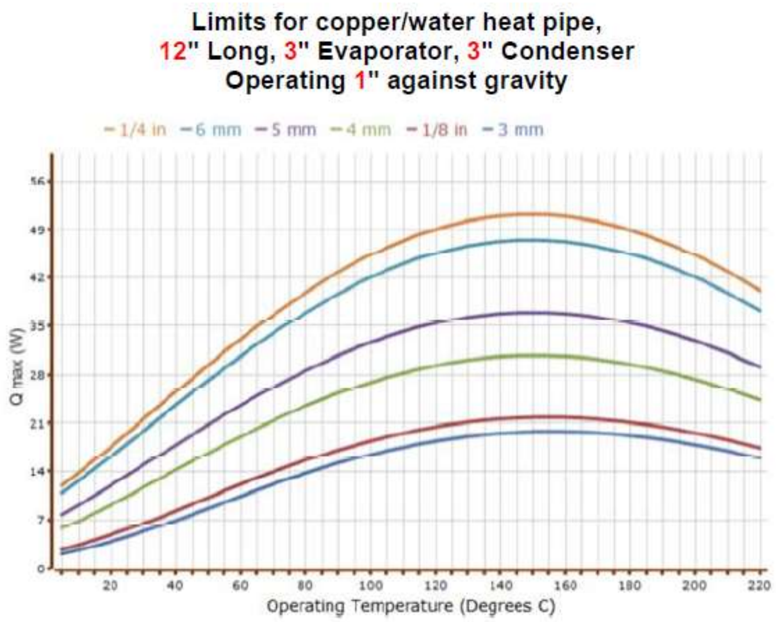






Heat Pipe Performance

- Heat pipe performance peaks somewhere in the middle of the temperature range
  - High vapor pressure drops (sonic limit) at low end
  - Increase in vapor density and reduction in liquid viscosity help in the middle
  - Reduction in latent heat and surface tension hurts at the high end



Envelope/Fluid Selection

- Envelope/Fluid Selection depends on two things
  - Fluid Properties
  - Compatibility of the Fluid with the wall and the wick
- Compatibility Determined by Life Tests
  - Discussed Below
- Fluid Selection
  - Freezing temperature below minimum operating temperature
  - Critical temperature above maximum operating temperature
    - Pressure containment
    - Capillary pumping capability is zero at $T_{Critical}$
  - Desirable Fluid Properties
    - High surface tension
    - High density
    - High Latent Heat
    - Low Viscosity
  - Merit Number used to rank

Merit Number

- Merit Number used to help select fluid
- Neglect gravity, assume all pressure drop is in the liquid flow (Darcy)

$$\Delta P_l = \frac{\dot{m}\ \mu_l\ L_{Effective}}{\rho_l\ k_{wick}\ A_{wick}} \qquad \dot{m} = \frac{Q}{\lambda} \qquad \Delta P_l = \frac{2 \cdot \sigma}{r_c}$$

$$Q = \frac{2\ A_{wick}\ k_{wick}}{r_c\ L_{Effective}} \frac{\rho_l\ \sigma\ \lambda}{\mu_l}$$

Second Term – Fluid Properties

- Merit Number

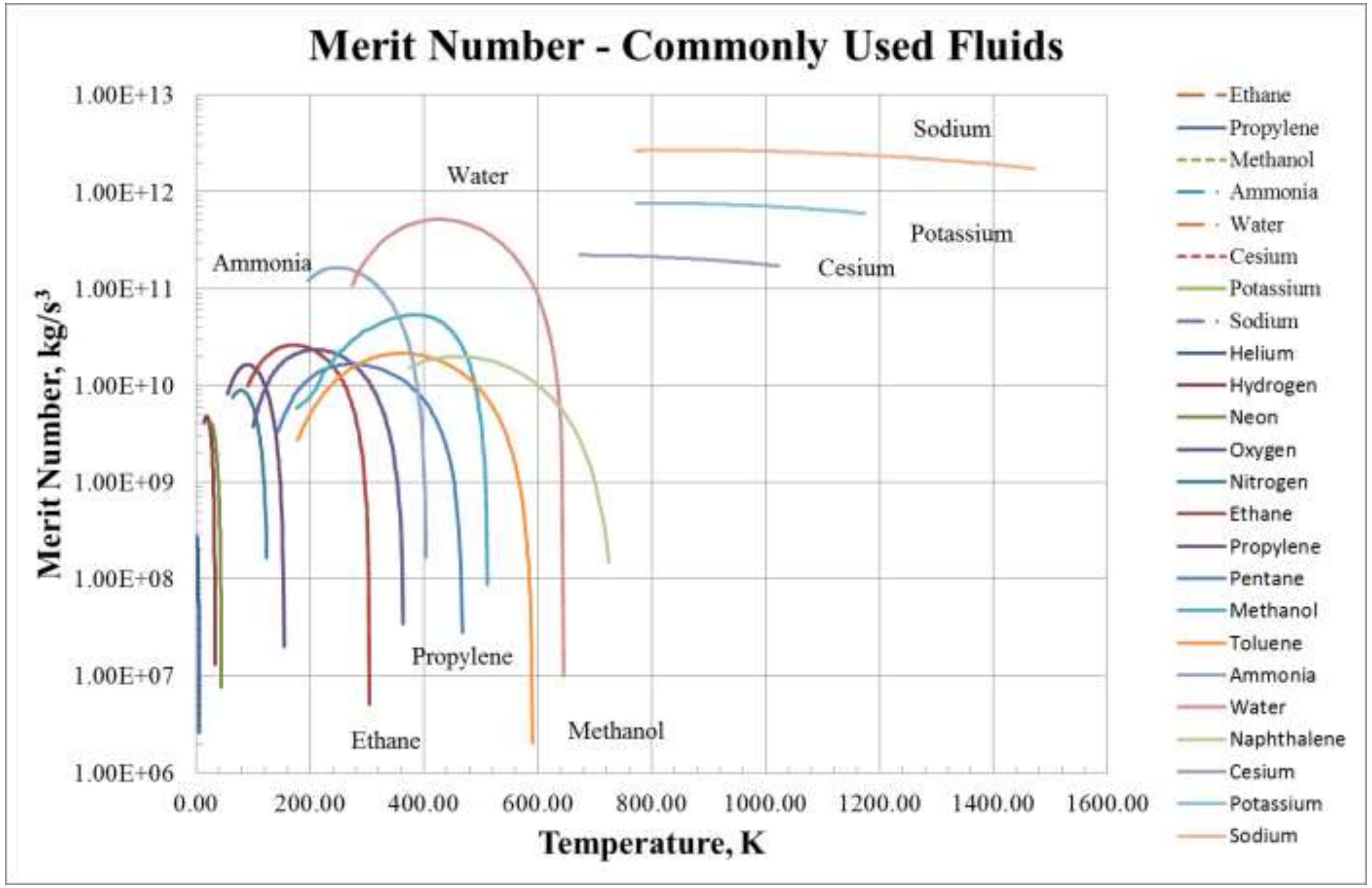
$$N_l = \frac{\rho_l \sigma \lambda}{\mu_l}$$

High liquid density, high latent heat, and low liquid viscosity reduce liquid pressure drop

High surface tension increases pumping capability

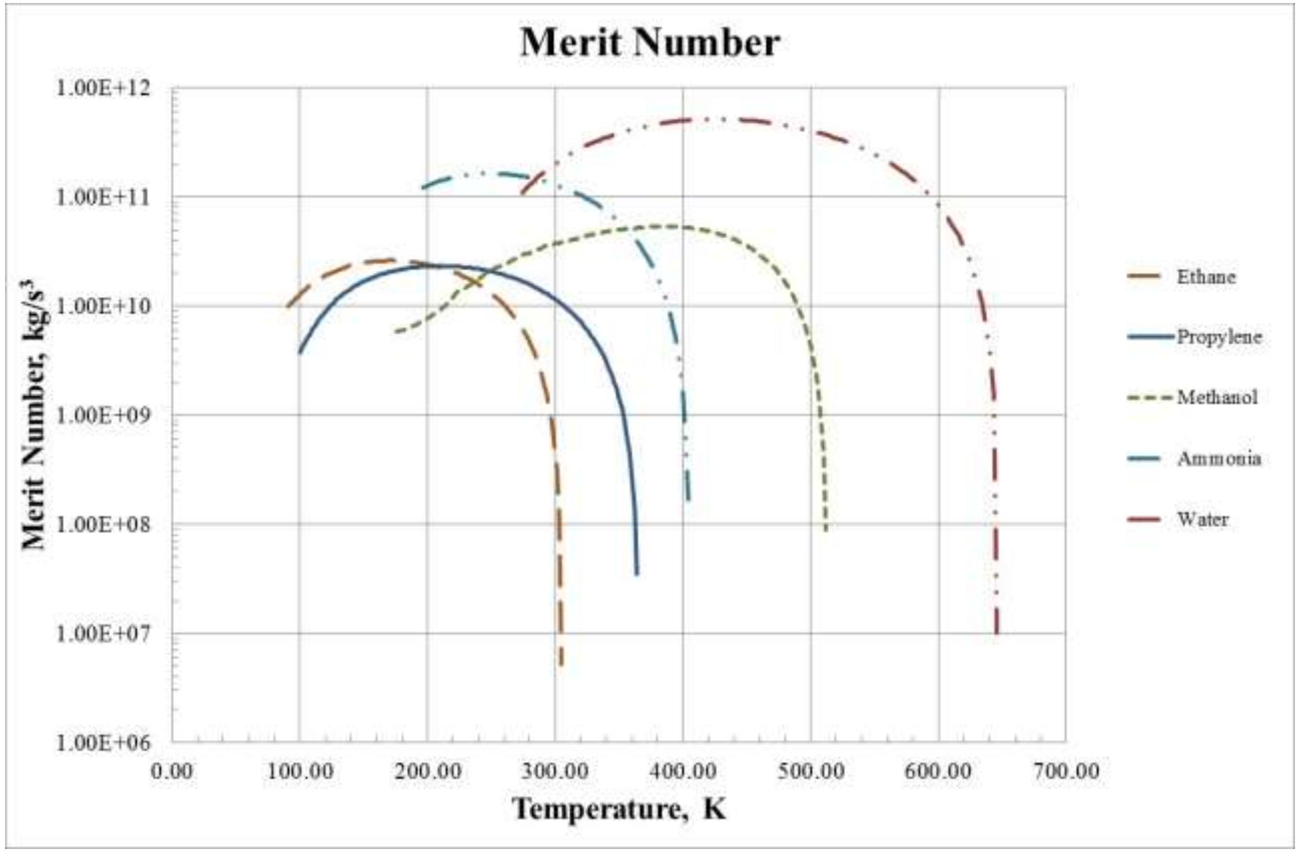
Merit Number

- Merit Number helps explain why cryogenic heat pipes carry ~ 1 W, water carries 100 W, and alkali metal pipes carry 1000 W



Merit Number

- Prefer to use water for electronics cooling
  - Merit number ~10 times higher than everything else except the liquid metals
- Ammonia better for lower temperatures – used in spacecraft CCHPs



Most Commonly Used Fluid/Material Pairs

- Electronics Cooling
  - Copper/Water – probably 99+% of all heat pipes
  - Titanium/Water and Monel/Water at Higher Temperatures (>150°C, or to reduce mass)
  - Copper/Methanol when the heat pipe must operate below ~ 15-20°C

- Spacecraft Thermal Control (6061, 6063 Aluminum, 316L SS)
  - Aluminum/Ammonia Heat Pipes, Aluminum/Steel/Ammonia LHPs
  - Aluminum/Steel/Propylene LHPs at Lower Temperatures
  - Aluminum/Ethane CCHPs at Lower Temperatures

Most Commonly Used Fluid/Material Pairs

- HVAC
  - Copper or Steel with R134a
- High Temperature
  - Stainless Steels and Superalloys with alkali metals (Cs, K, and Na (*not* Li))
    - Up to 1100°C with Haynes 230 for short times (creep strength)
  - Refractory Metals/Alkali Metals (Na, Li) at Higher Temperatures
  - Systems must be oxygen free for long-life
    - Sometimes use getters to scavenge oxygen in refractory metal heat pipes

Potential Problems

- Aluminum/water
  - Water reacts with aluminum, forms NCG very quickly
- Aluminum/methanol, aluminum/ethanol
  - Methanol and ethanol also react with the aluminum
- Copper/Ammonia
- Steel/Ammonia
  - 316L is compatible, 316 may cause gas generation
- Steel/Water
  - Incompatible
  - Others have claimed is compatible with additives
  - ACT hasn't built any steel/water pipes that worked
- Mercury (wetting), Sulfur/Iodine (corrosion)

Fluid/Envelope Recommendations

Operating Min Temp.	Operating Max Temp.	Working Fluid	Envelope Materials	Comments
-271	**-269**	Helium	Stainless Steel, Titanium	
-258	**-243**	Hydrogen	Stainless Steel	
-246	**-234**	Neon	Stainless Steel	
-214	**-160**	Oxygen	Aluminum, Stainless Steel	
-203	**-170**	Nitrogen	Aluminum, Stainless Steel	
-170	**0**	Ethane	Aluminum, Stainless Steel	CCHPs below Ammonia Freezing point
-150	**40**	Propylene	Aluminum, Stainless Steel, Nickel	LHPs below Ammonia Freezing point
-100	**120**	Pentane	Aluminum, Stainless Steel	
-80	**50**	R134a	Stainless Steel	Used in Energy Recovery
-65	**100**	Ammonia	Aluminum, Steel, Stainless Steel, Nickel	Copper, titanium are not compatible
-60	**~ 100 to 25**	Methanol	Copper, Stainless Steel	Gas observed with Ni at 125°C, Cu at 140°C. Aluminum and titanium are not compatible
-50	**~ 100**	Acetone	Aluminum, Stainless Steel	Decomposes at higher temperatures

Fluid/Envelope Recommendations

Operating Min Temp.	Operating Max Temp.	Working Fluid	Envelope Materials	Comments
-50	**280**	Toluene	Al at 140°C, Steel, Stainless Steel, Titanium, Cu-NI	Gas generation at higher temperatures (ACT life test)
20	**280, short term to 300**	Water	Copper, Monel, Nickel, Titanium	Short term operation to 300°C. Aluminum, steels, stainless steels and nickel are not compatible
100	**350**	Naphthalene	Al, Steel, Stainless Steel, Titanium, Cu-Ni	380°C for short term. Freezes at 80°C
200	**300, short term to 350**	Dowtherm A/Therminol VP	Al, Steel, Stainless Steel, Titanium	Gas generation increases with temperature. Incompatible with Copper and Cu-Ni
200	**400**	$AlBr_3$	Hastelloys	Aluminum is not compatible. Freezes at 100°C
400	**600**	Cesium	Stainless Steel, Inconel, Haynes, Titanium	Upper limit set by where K is the better working fluid. Monel, Copper, and Copper-Nickel are not compatible
500	**700**	Potassium	Stainless Steel, Inconel, Haynes	Upper limit set where Na is the better fluid. Monel and Copper are not compatible
500	**800**	NaK	Stainless Steel, Inconel, Haynes	Upper limit set where Na is the better working fluid. Monel and Copper are not compatible
600	**1100**	Sodium	Stainless Steel, Inconel, Haynes	Upper limit set by Haynes 230 creep strength
1100	**1825**	Lithium	Tungsten, Niobium. Molybdenum, TZM	Lithium not compatible with superalloys. Refractory metals react with air

- http://www.1-act.com/heat-pipe-materials-working-fluids-and-compatibility/
- http://www.1-act.com/compatible-fluids-and-materials/

Fine Print – Fluid/Envelope Recommendations

- All temperature ranges are approximate – you can generally go to lower temperatures with a larger diameter, and to higher temperature with a thicker wall
- Note: The table is generic. In most cases, only specific alloys are known to be compatible
  - Only certain Austenitic stainless steels are used with cryogenic heat pipes (many steels become extremely brittle below a certain temperature)
    - 304, 304L, 310, 347 retain good ductility at cryogenic temperatures
  - 6061 and 6063 Aluminum with ammonia and ethane (partially due to high conductivity, and the inherent conservatism of the spacecraft community)
  - CDA 101 Copper/water (due to processing with hydrogen)
  - Nickel is compatible with water at lower temperatures, but can split water at high temperatures

Fine Print – Fluid/Envelope Recommendations

- Note: The table is generic. In most cases, only specific alloys are known to be compatible
- Some superalloys (Hastelloys) with halides
  - Hastelloy B-3 (Ni-Mo)
  - Hastelloy C-2000 (Ni-Cr-Mo),
  - Hastelloy C-22 (Ni-Cr-Mo-W)
  - Others alloys may be compatible, but haven't been tested.
- 304L, 316L stainless steels, some superalloys with the alkali metals
  - Maximum temperature for Cs and K not a true limit, but determined by switching to a better working fluid (i.e. potassium beats cesium above 500°C)
  - Maximum temperature for Na set by creep strength of Haynes 230
  - Others alloys may be compatible, but haven't been tested.
  - Need to consider creep for sodium at the higher temperatures
  - Titanium has been tested with Cs and K, for relatively short times
    - Creep strength limits maximum temperature

Heat Pipe Working Fluids and Compatibility Takeaways

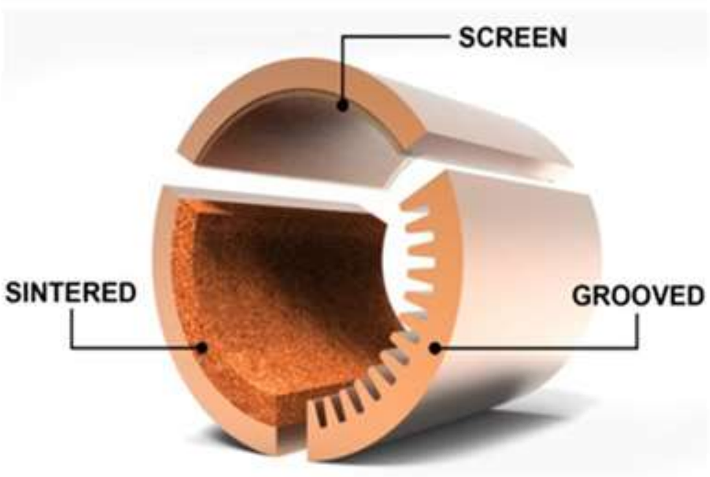
- Ammonia is the most commonly used fluid for spacecraft thermal control, with 6061, 6063 Aluminum, and 316L SS
  - Aluminum/Ammonia Heat Pipes, Aluminum/Steel/Ammonia LHPs
  - Aluminum/Steel/Propylene LHPs at Lower Temperatures
  - Aluminum/Ethane CCHPs at Lower Temperatures
- Copper/Water is the most commonly used fluid/envelope pair for electronics cooling
  - Recently extended into spacecraft
  - Methanol/Copper used when need to operate at lower temperatures
- Alkali metal/Superalloy systems are used at temperatures above 400°C
  - Spacecraft fission and radioisotope power, nuclear propulsion
- More Information: https://www.1-act.com/innovations/heat-pipe-materials-working-fluids-and-compatibility/

Heat Pipe Wicks

- Wick Types:
  - Grooved Wick
  - Screen Wick
  - Sintered Wicks
  - Hybrid Wicks

Wick Types

- Three primary wick types
  - Screen
    - Lowest cost
    - Earth and space based electronics cooling
    - Low pressure drop
    - Moderate capillary action
  - Sintered
    - High performance
    - Moderate pressure drop
    - Highest capillary action
    - Suitable for higher accelerations
  - Grooved
    - High power in low acceleration environments (low earth orbit)
    - Lowest pressure drop
    - Lowest capillary action
    - Can be made from sintered powder or solid extrusion
  - Hybrid – Combine Two Wick Types

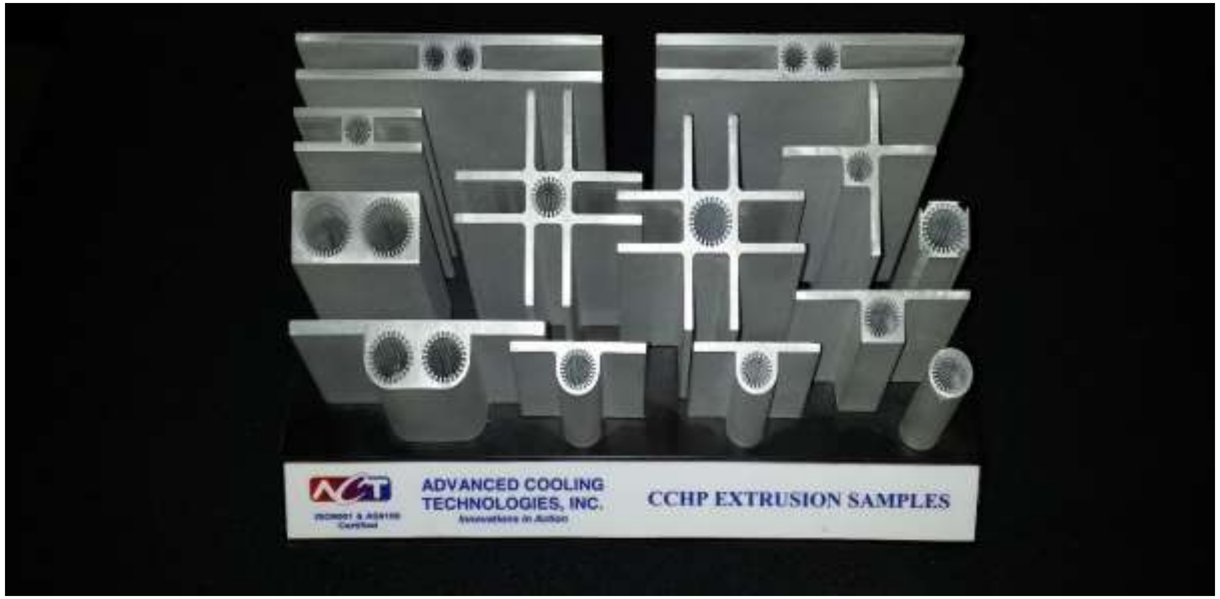


Wick Trade-Offs

- Small pores provide good lift height, but lower power – because the liquid flow is restricted by difficulty of getting through the small pores
  - Small pores have high flow resistance – resulting in short heat pipes
  - Greater ability to operate against gravity
  - Small pores usually provide high power density (q/a, or watts per square centimeter)
- Large pores usually permit large liquid flow with high total power transferred, but poor lift height
- Long heat pipes require wick structures with low flow resistance
  - Good wicks for long heat pipes include: grooves, coarse screen, various composites
  - Only operate slightly against gravity
  - Aerospace CCHPs typically tested 0.1 inch against gravity (to avoid puddle flow)
- Rule of Thumb
  - Start with the largest pore size that can handle the gravitational head
  - Decrease pore size until you hit the maximum power

Axial Grooves

- Almost all spacecraft heat pipes use grooved aluminum extrusions
- High power in low acceleration environments (low earth orbit)
- Lowest pressure drop
- Lowest capillary action
- Dual Bore Extrusion used for higher capacity, or to provide redundancy

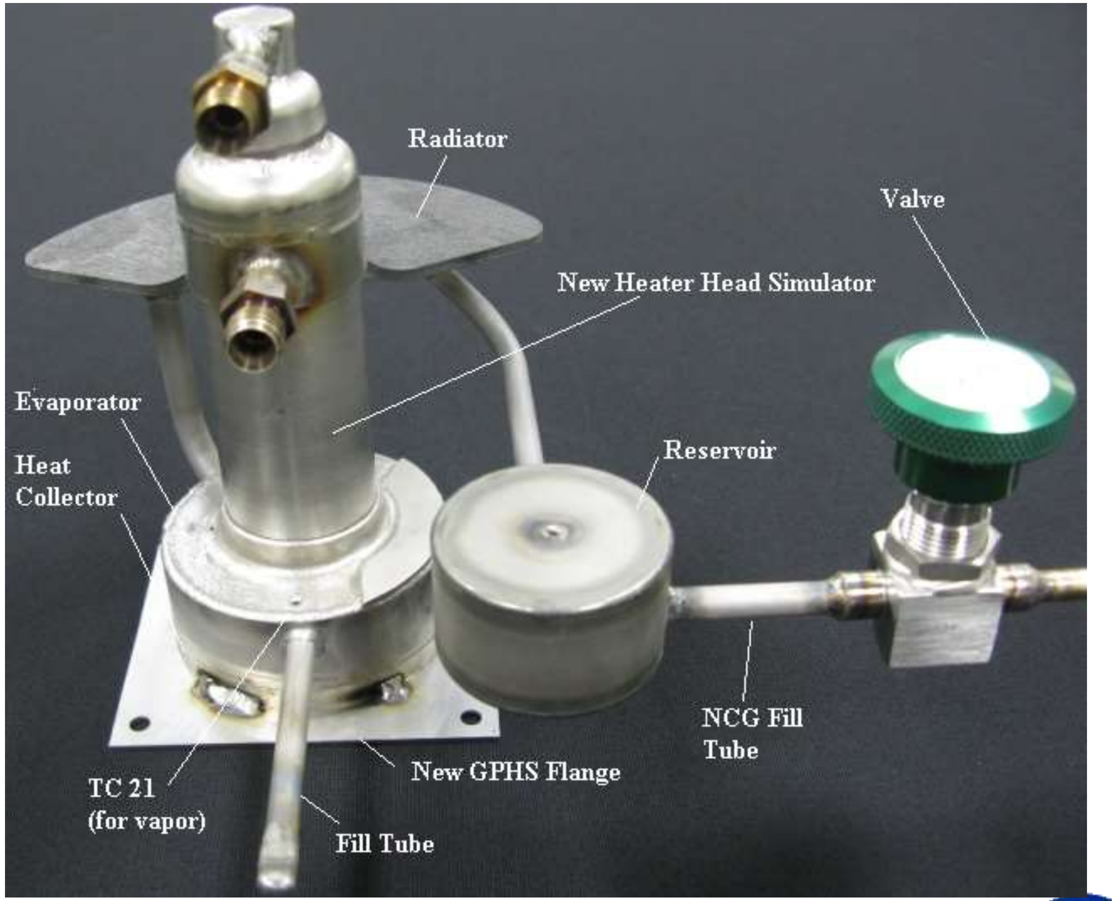


Wick Selection – Screen

- Screen heat pipes are the standard wick at ACT for
  - Copper/water heat pipes
  - HiK plates
  - IFLs
  - Other heat pipes with complicated shapes
- Lowest cost
- Low pressure drop
- Moderate capillary action
- Screens specified by mesh size
  - 100 x 100 mesh size means 100 wires per inch in both directions
  - Available wire sizes vary by demand, and by ductility of the material
  - 150 mesh Titanium, 200 mesh Phosphor Bronze, 400 mesh Monel, 1000 mesh SS available
- Spot weld or sinter screen to envelope

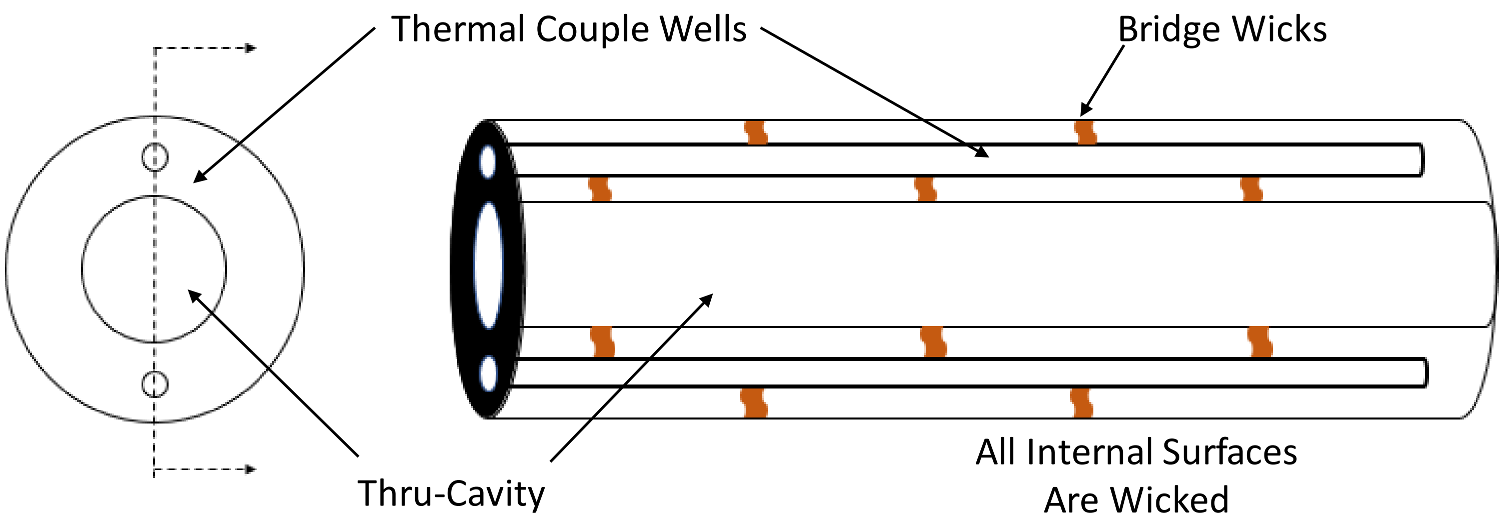
Alkali Metal VCHP with Screened Wick

- VCHP has two condensers, and a wicked reservoir
  - Screen is the only suitable wick



Screen Wicks for Annular Heat Pipes

- Annular Heat Pipes are primarily used for Temperature Calibration
  - Place in furnace, with non-uniform heat flux on the outside
  - Very isothermal interior
- Need to return liquid from inside to outside with bridge wicks
  - Use screen to accommodate the changing diameters of the inner and outer cylinders (variable distance in the gap) as the system heats up



Wick Selection – Screen

- Screen properties can be estimated empirically
  - Heat Pipe Theory and Practice - Chi

$$\mathrm{Spacing}_{\mathrm{Wire}} = \frac{1 - \mathrm{MeshSize} \cdot \mathrm{Diameter}_{\mathrm{Wire}}}{\mathrm{MeshSize}}$$

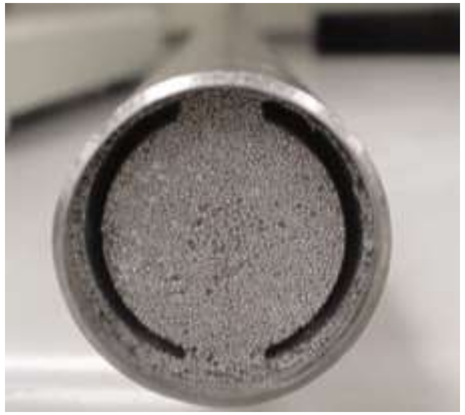
$$\mathrm{Pore}_{\mathrm{Radius}} = \frac{1}{2 \cdot \mathrm{MeshSize}}$$

$$\mathrm{Porosity} = 1 - \frac{1.05\pi \cdot \mathrm{MeshSize} \cdot \mathrm{Diameter}_{\mathrm{Wire}}}{4}$$

$$\mathrm{Permeability} = \frac{\mathrm{WireDiameter}^2 \cdot \mathrm{Porosity}^3}{122 \cdot (1 - \mathrm{Porosity})^2}$$

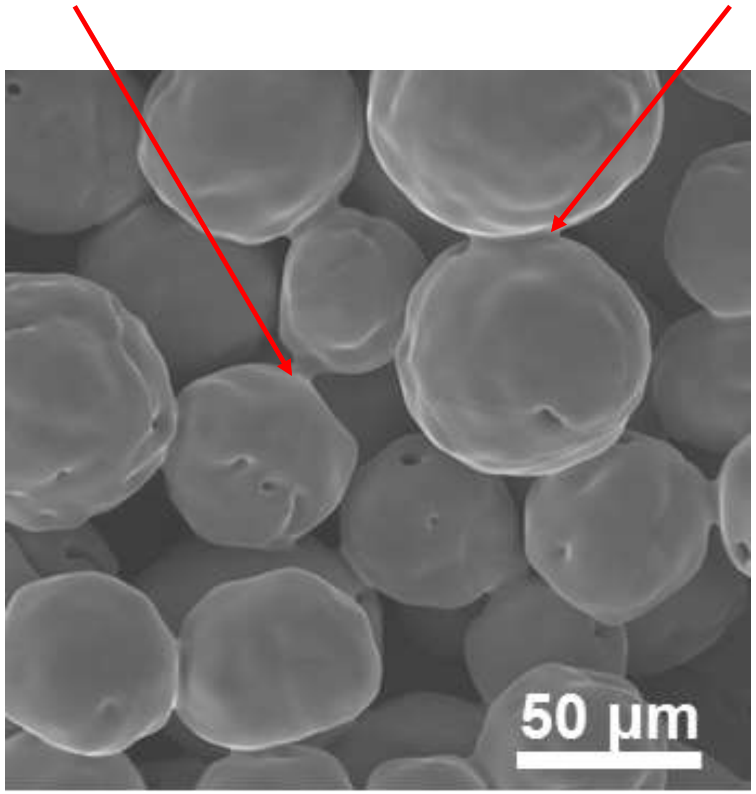
Wick Selection - Sintered

- High performance
  - Used at heat pipe companies for high volume heat pipe production
- Moderate pressure drop, Highest capillary action
- Suitable for higher accelerations and higher heat fluxes than screen or grooved wicks
- Compared to screen or grooves, more variation in pore size and permeability from heat pipe to heat pipe
- Suitable for simple shapes
  - Round
  - Flattened
  - High Heat Flux Vapor Chambers
- Specialty designs where wick occupies most of the heat pipe



Sintered Heat Pipe Wicks

- When clean metal particles are heated to about 80% of their melting temperature, they start to sinter together
  - Similar to ice cubes in a freezer bonding together (within 20°C of the melting point)
- Sintering is driven by a reduction in surface energy
  - Atoms from adjacent particles form bonds
  - Powder particles start to fuse together
- Sintered wicks typically have a porosity of roughly 45%
  - Porosity similar to close packed spheres
  - Can be as high as 65-70% for LHP wicks with filamentous wicks
  - In contrast, most industries sinter to near 100% density
    - Higher temperatures and pressures

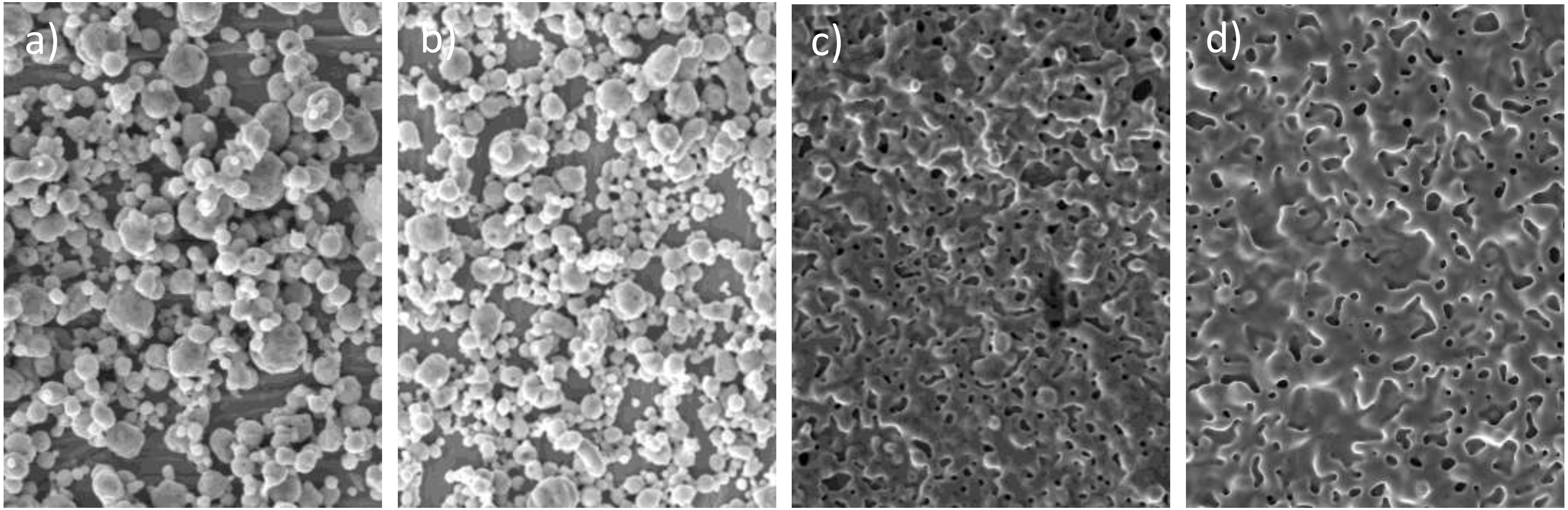


Sintered spherical copper powder, showing bridge formation

Sintering Results Depend on Time & Temperature

- Sintered copper powder on a flat surface
- (c) and (d) are over sintered

550°C and 2x sintering time | 625°C and 2x sintering time | 700°C and 2x sintering time | 775°C and 2x sintering time



Sintered Powder Sizes

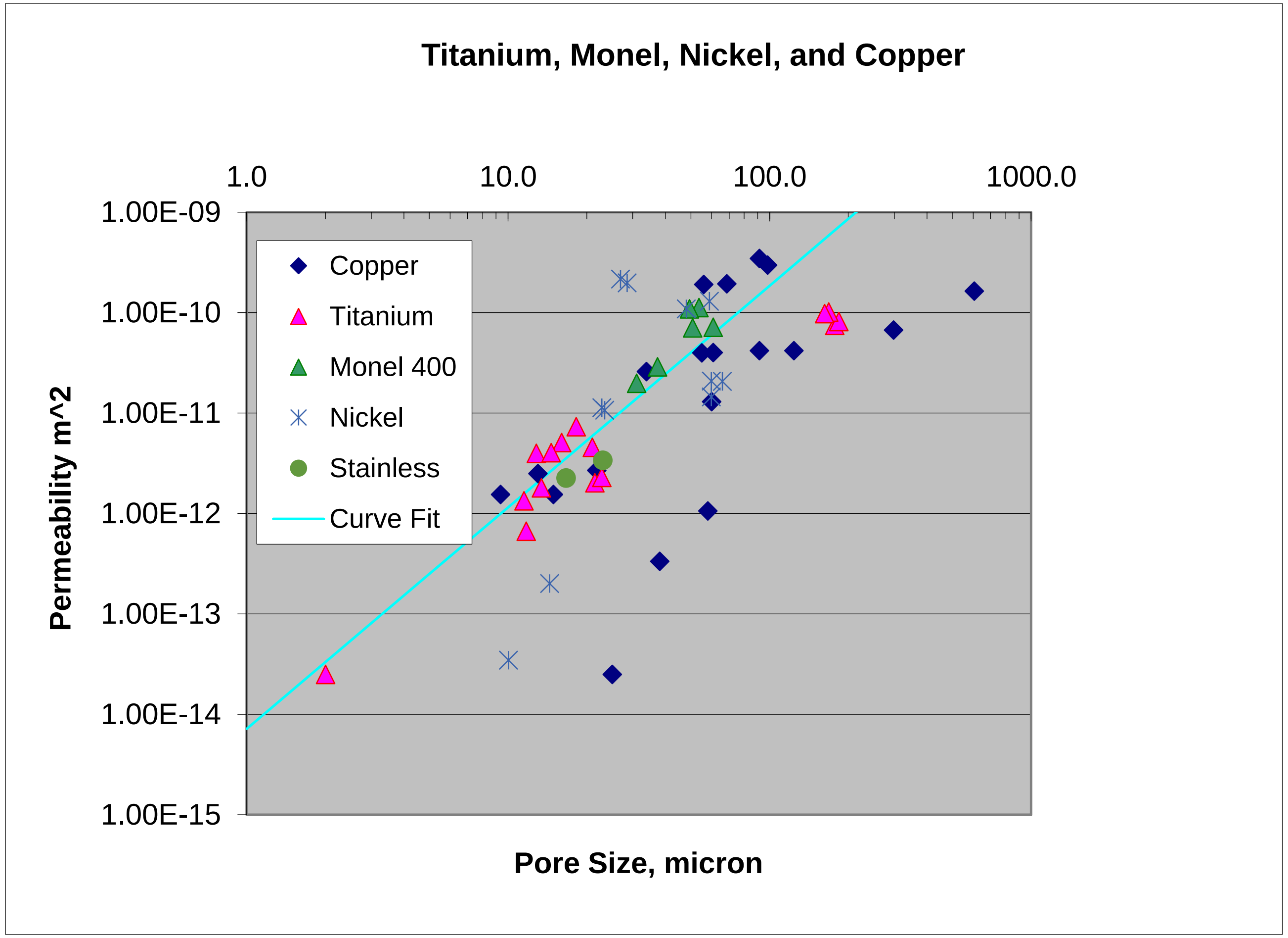
- Sintered powders available range from spheres with fairly uniform sizes to irregular particles with a wide size distribution
  - Fairly uniform powder size is generally desirable
  - With non-uniform powders, fine particles can clog up the larger pores
  - Reduces permeability
- Sift most powders through a series of screens, and only use a specified fraction
  - Coarse screens on top, graded to fine screens on the bottom
  - Vibrate powder, let it sift through screens
  - Screens specified in terms of mesh size (holes/inch)
- Powders specified in terms of mesh size
- -35+100 mesh powder means that the powder particles passed through a 35 mesh screen, but were stopped by a 100 mesh screen
  - Particles roughly smaller than 35 mesh, larger than 100, but actual sizes depend also on particle shape

Sintered Powder Sizes

		Opening				Opening	
U.S. Sieve	Tyler	mm	in	U.S. Sieve	Tyler	mm	in
No. 35	32 Mesh	0.5	0.0197	No. 120	115 Mesh	0.125	0.0049
No. 40	35 Mesh	0.42	0.0165	No. 140	150 Mesh	0.105	0.0041
No. 45	42 Mesh	0.354	0.0139	No. 170	170 Mesh	0.088	0.0035
No. 50	48 Mesh	0.297	0.0117	No. 200	200 Mesh	0.074	0.0029
No. 60	60 Mesh	0.25	0.0098	No. 230	250 Mesh	0.063	0.0025
No. 70	65 Mesh	0.21	0.0083	No. 270	270 Mesh	0.053	0.0021
No. 80	80 Mesh	0.177	0.007	No. 325	325 Mesh	0.044	0.0017
No.100	100 Mesh	0.149	0.0059	No. 400	400 Mesh	0.037	0.0015

Pore Size versus Permeability

- Anderson Curve: Pore Size and Permeability are Directly related



$$K = 0.125 \cdot r_c^{2.207}$$

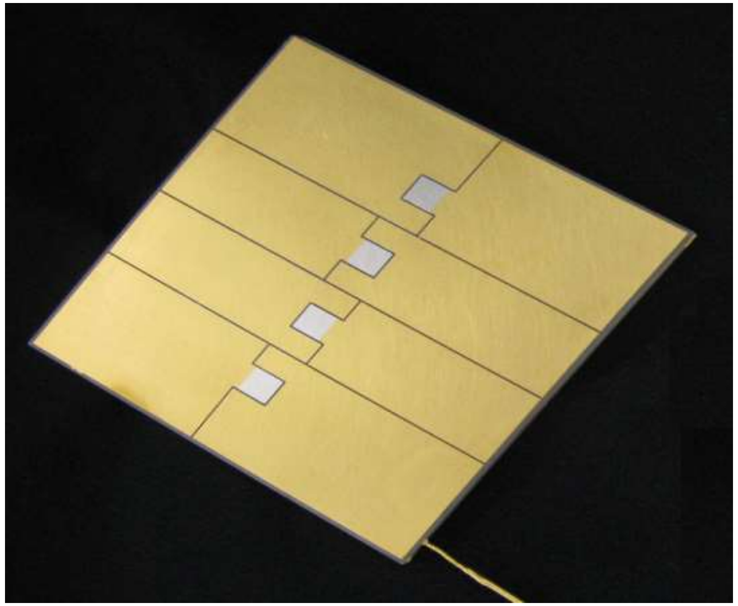
Permeability: m^2

Pore Size: µm

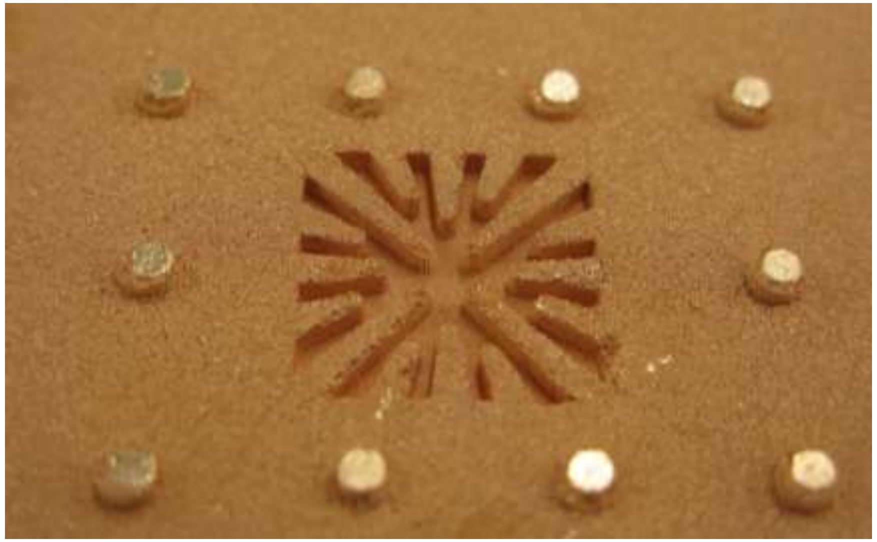
Hybrid Wick Heat Pipes

- Combine Two or More Different Wicks
- High-Heat-Flux Vapor Chambers
  - Sintered Thick and Thin Layers
- Flexible Heat Pipes
  - Screen Evaporator/Cable Artery/Grooved Condenser
- Sintered/Screen and Grooves
  - High Heat Flux CCHPs
  - Lunar and Martian Landers and Rovers

High Heat Flux Vapor Chambers

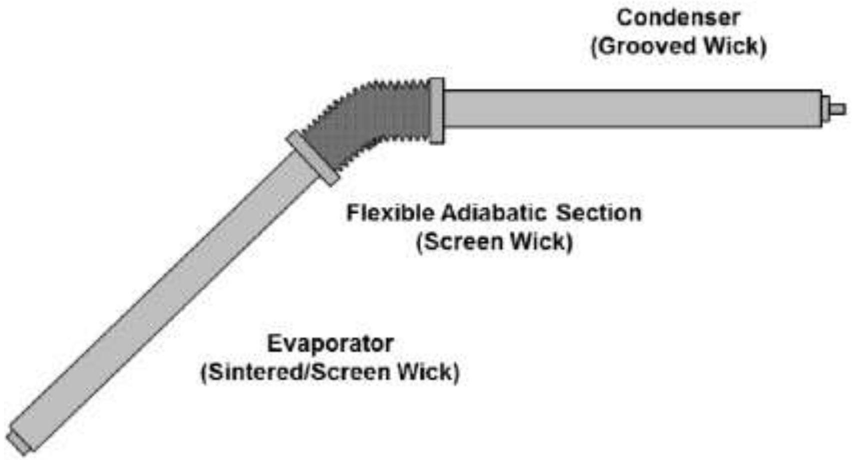


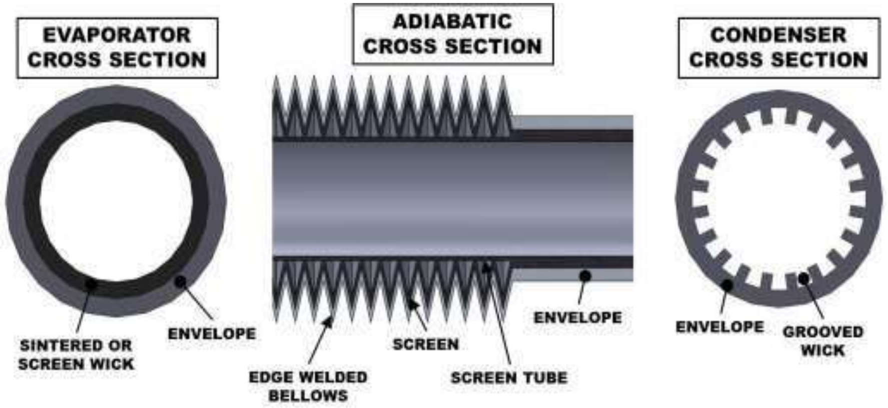
- Laser Diodes have high heat fluxes, and should be isothermal
- Direct-Bond-Copper Vapor Chamber
- Etch off copper to electrically isolate each diode.
- High heat flux wicks operate by separating the liquid return structure (arteries) from the heat transfer structure (monolayer)



Flexible CCHP Basic Concept

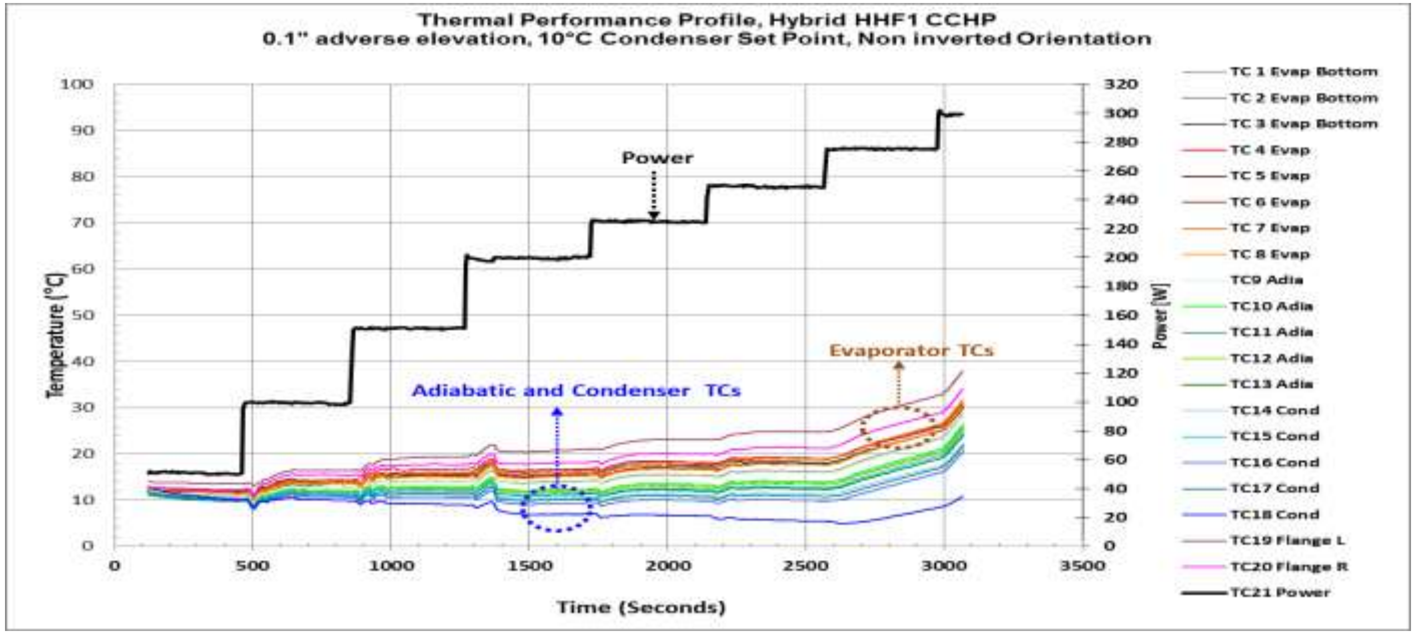
- The proposed heat pipe is composed of at least three sections, utilizing a hybrid wick for optimal performance.
- To ensure liquid flow from the condenser, through the bellow section, and to the evaporator, the effective pore radius must decrease in the same order.
  - Condenser wick will be grooved.
  - Adiabatic can be screen or a cable artery
  - Evaporator wick can either be screen or sintered as long as the effective pore radius is the smallest in the CCHP.





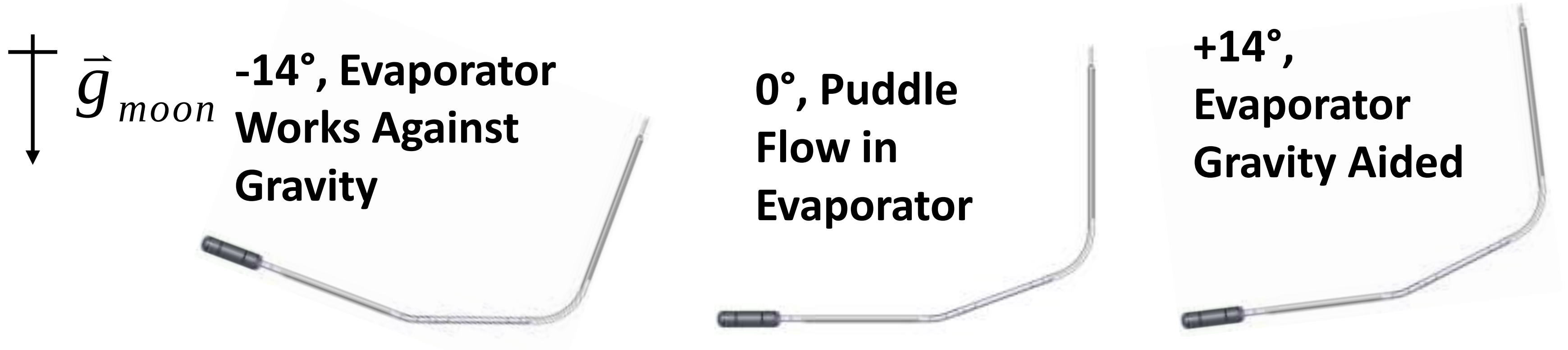
High Heat Flux CCHPs

- High Heat Flux CCHP has a sintered wick in the evaporator, and grooves in the rest of the heat pipe
- Evaporator: Small Pore size – High Heat Flux, Low Permeability
- Condenser: High Permeability, Low Pumping Capability
- Suitable for high heat flux heat pipes
- Hybrid wick high heat flux aluminum/ammonia CCHP transported a heat load of **275 Watts with heat flux input of 54 W/cm² and R=0.015 ºC/W at 0.1 inch adverse elevation.**
- This demonstrates an improvement in heat flux capability of more than ***3 times*** over the standard axial groove CCHP design.



Hybrid Wicks for Landers and Rovers

- Standard VCHPs use grooved wick - not suitable for Moon
    - 0.1 inch against gravity
- Tilt range for lunar surface: up to ±45° for Rovers
- VCHP evaporator needs to operate against gravity
    - Maximum adverse elevation: (9 inch) × sin(14°) = 2.2 inch
- Screen or Sintered wick in evaporator; Grooved wick in condenser
    - Grooves and screen pump in space
    - Screen pumps on lunar surface



Heat Pipe Wicks – Takeaways

- Types of Wicks include grooved, screen, sintered, and hybrid
- Grooved wicks typically used for spacecraft
  - Max heat flux ~ 10 W/cm^2
- Screen Wicks used for low volume and complicated shapes
  - Max heat flux ~ 75 W/cm^2
- Sintered used for high volume production
  - Max heat flux ~ 75 W/cm^2, 1000 W/cm^2 for specialized wicks
- Hybrid Wicks have different wicks in the evaporator and condenser
  - High Heat Flux Vapor Chambers ~ 750 W/cm^2 and CCHPs ~50 W/cm^2
  - Flexible Heat Pipes
  - Heat Pipes for Lunar and Martian Landers and Rovers

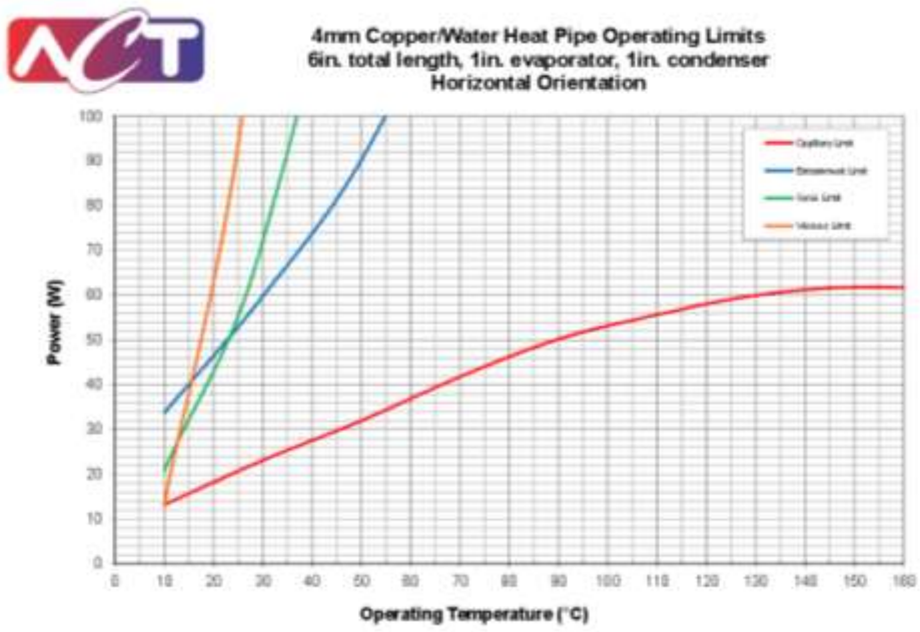
Heat Pipe Modeling

- Heat Pipe Calculator (Copper/Water)
- Simple Model (Copper/Water)
- Assembly Modeling (heat pipe as thermal link in larger thermal systems)
  - ACT's classical method based on heat pipe solid cores with equivalent conductance
    - When variable conductance is involved – integrated (external-simplified) modeling becomes more difficult

Heat Pipe Modeling

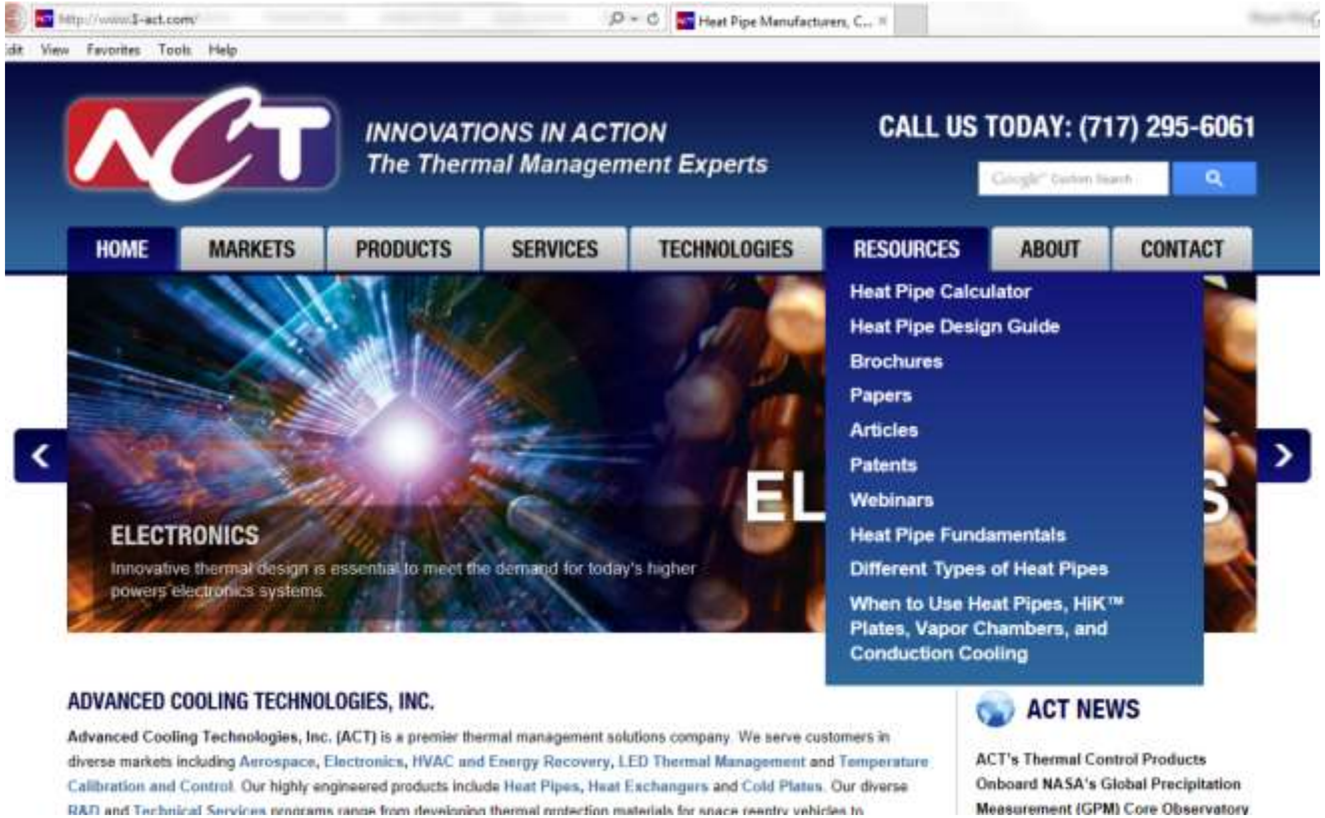
- Theoretically, heat pipes could be modeled with a very elaborate two-phase flow model in a high end CFD program
- This is never done, since the model would be very complicated, and take a long time to run
- Instead, the heat pipe model is broken into two parts

1. Heat Pipe Limit Calculations
    - Simple set of 1-D equations that determine the maximum power that the heat pipe can carry as a function of temperature
2. Detailed CFD thermal model of the Assembly
    - Neglects two phase flow – replaces with a high conductivity solid to simulate heat transfer in the vapor space
    - After the CFD calculations, need to check to make sure the maximum power is not exceeded

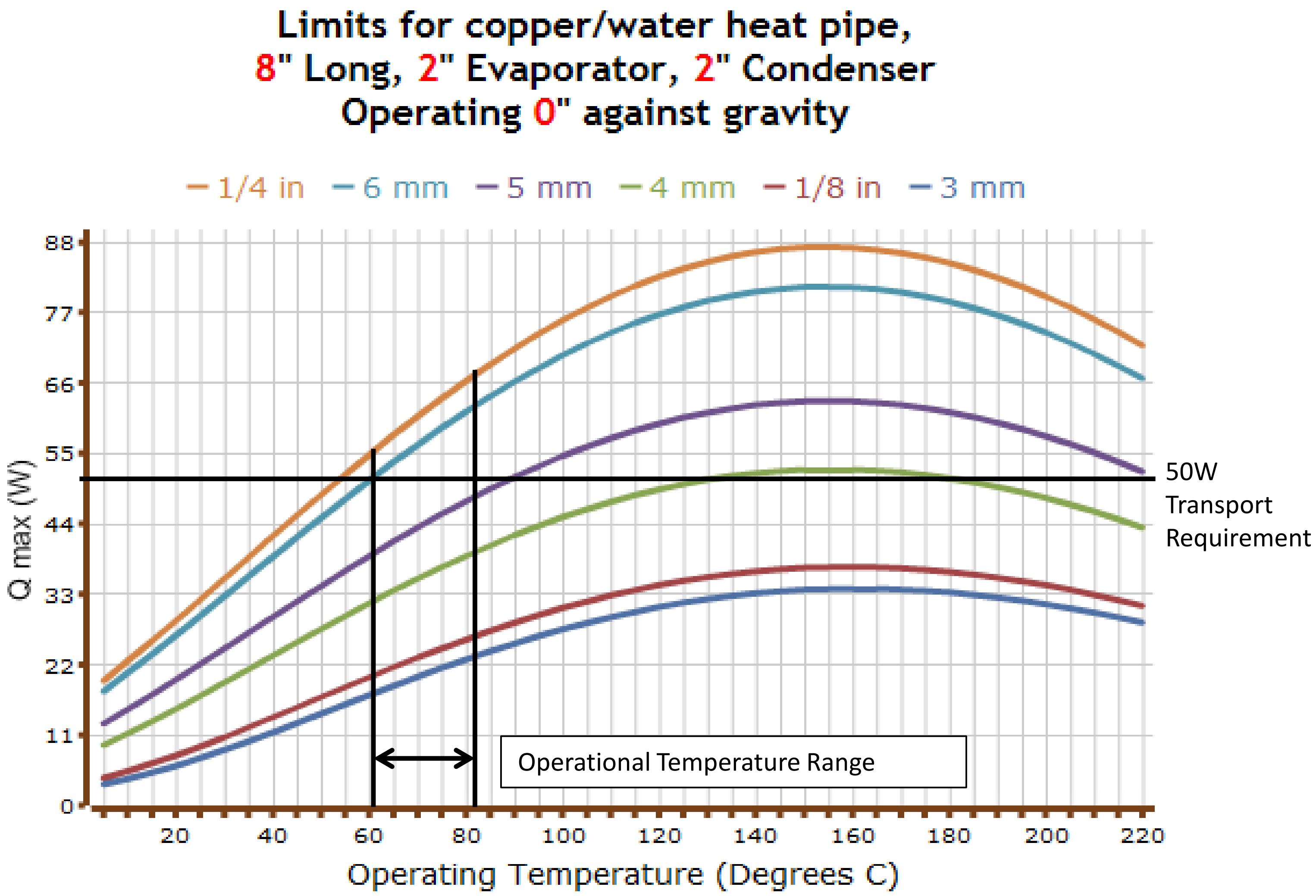


Online Water Calculator Resource

- ACT offers a free, no sign-up online calculator
  - Resources → Heat Pipe Calculator

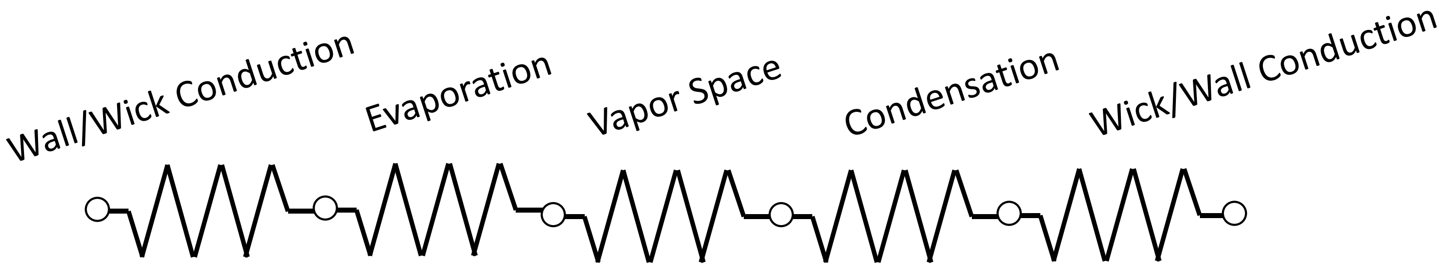


Heat Pipe Calculator Example



Thermal Resistance Network

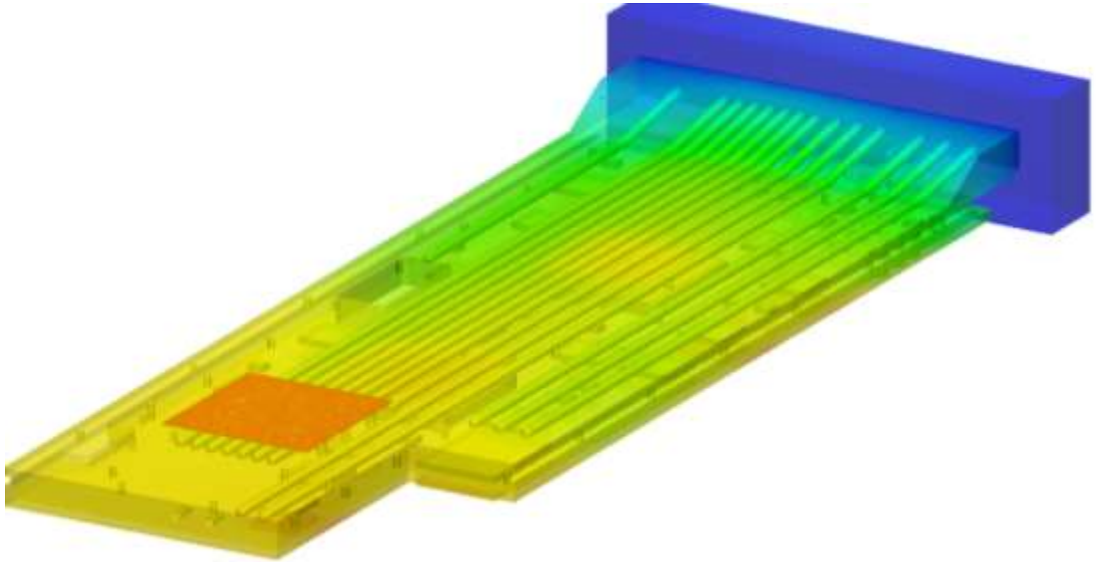
- In a properly designed heat pipe, the maximum power is set by the source and sink conditions, and the temperature drops across the heat pipe:
  - Conduction through the envelope wall and wick
  - Evaporation
  - Vapor Space Temperature Drop
  - Condensation
  - Conduction through the envelope wick and wall



$$\frac{ln\left(\frac{r_o}{r_i}\right)}{2\pi l_e k} \qquad \frac{1}{2\pi r_i l_e h_e} \qquad \frac{l}{\pi {r_i}^2 k_{eff}} \qquad \frac{1}{2\pi r_i l_c h_c} \qquad \frac{ln\left(\frac{r_o}{r_i}\right)}{2\pi k l_e}$$

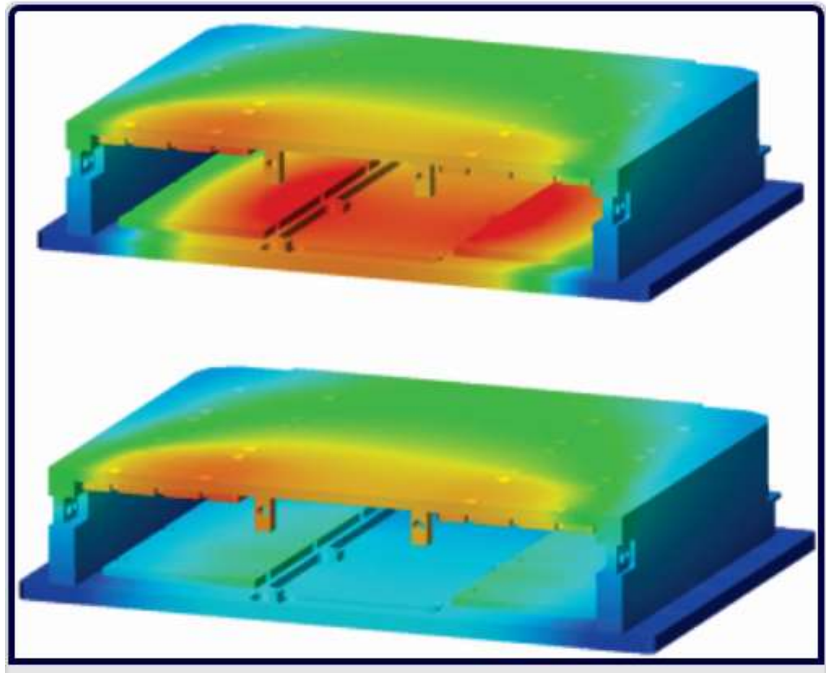
Basic Heat Pipe Modeling – Conduction Rod

- Assume a 2-5 ˚C temperature rise to account for your heat pipe – typical
- Bend and Flatten heat pipe so that it fits into your system
- Model heat pipe as a solid rod in your system and assign an initial thermal conductivity
    1. Start with k=10,000 W/m-K
    2. Check max temperature on heat pipes
    3. Iterate changing k until max temperature difference is 2-5 ˚C



Basic HiK™ Plates

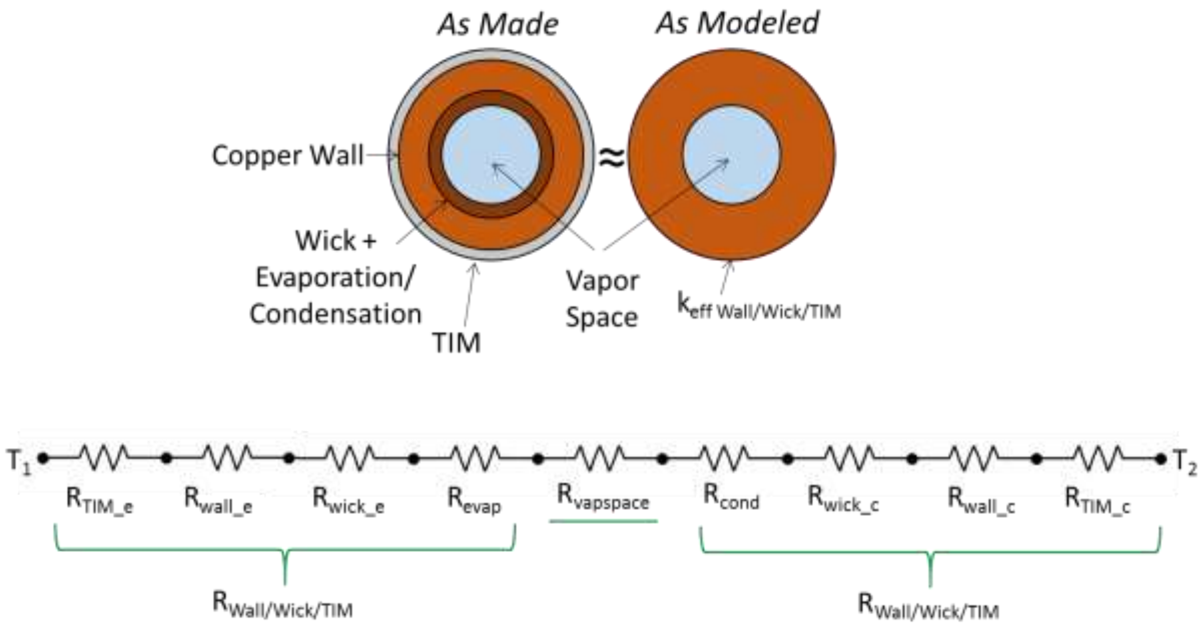
- Over many programs, ACT has matched test data to a range of effective thermal conductivities for HiK™ Plates.
  - k = 500 to 1,200 W/m-K
  - Depends on
    - geometry
    - sink conditions
- Model HiK™ plate as solid plate
- **Assign a thermal conductivity of 600 W/m-K**
  - If you're close to your desired results, heat pipes can probably be optimized to meet your goals



Replaced Baseplate w/ HiK™ Plate

Modeling Heat Pipe Assemblies

- Model the heat pipe using two components
- Heat Pipe Envelope
  - Captures radial thermal resistance
  - Includes TIM, Heat Pipe Wall, Wick, and Evaporation/Condensation Thermal Resistance
  - Relatively low effective thermal conductivity



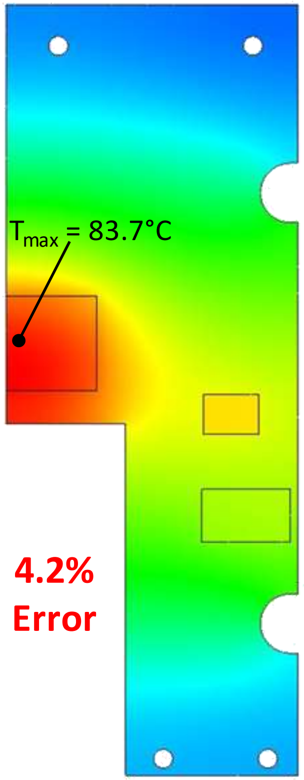
Modeling Heat Pipe Assemblies

- Vapor Space:
  - Simulates the effects of two phase heat transfer using conduction elements
    - Significantly simplifies model
  - Uses known geometry (l_{eff} and A), power (Q), and vapor space ΔT to back-calculate k_{eff}
  - High axial conductivity
    1. Start with k=10,000 W/m-K
    2. Check max temperature on heat pipes
    3. Iterate until max temperature difference is 2-5 ˚C
  - For a detailed explanation, see the following webinar:
  - https://www.1-act.com/act-webinars/heat-pipe-design-and-modeling/

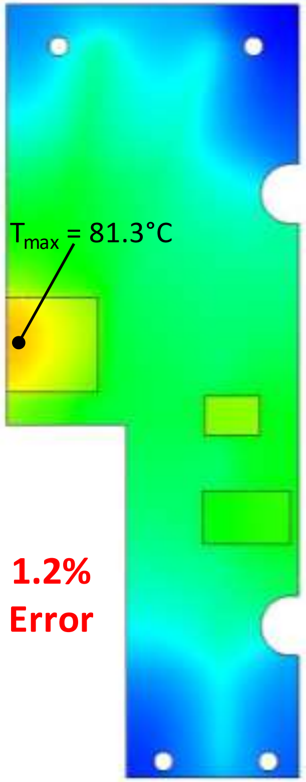
Modeling Heat Pipe Assemblies

- More complex modeling gives better results

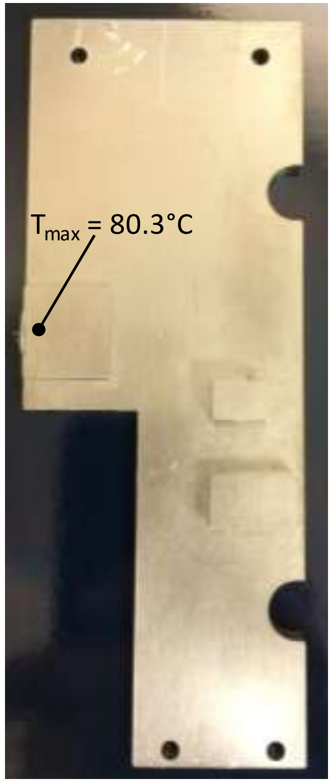
Modeled k_{eff}= 500 W/m-K

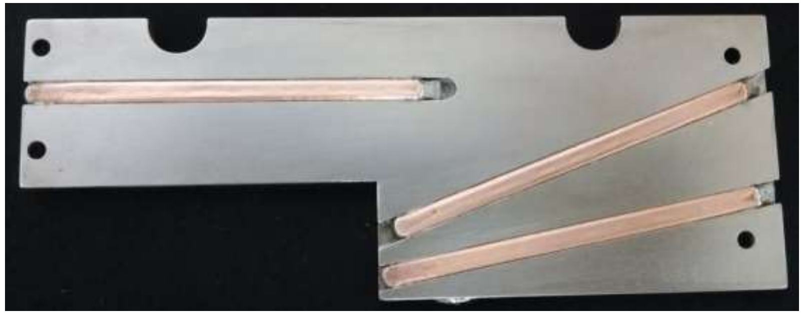


Modeled using Complex Modeling Approach



Tested



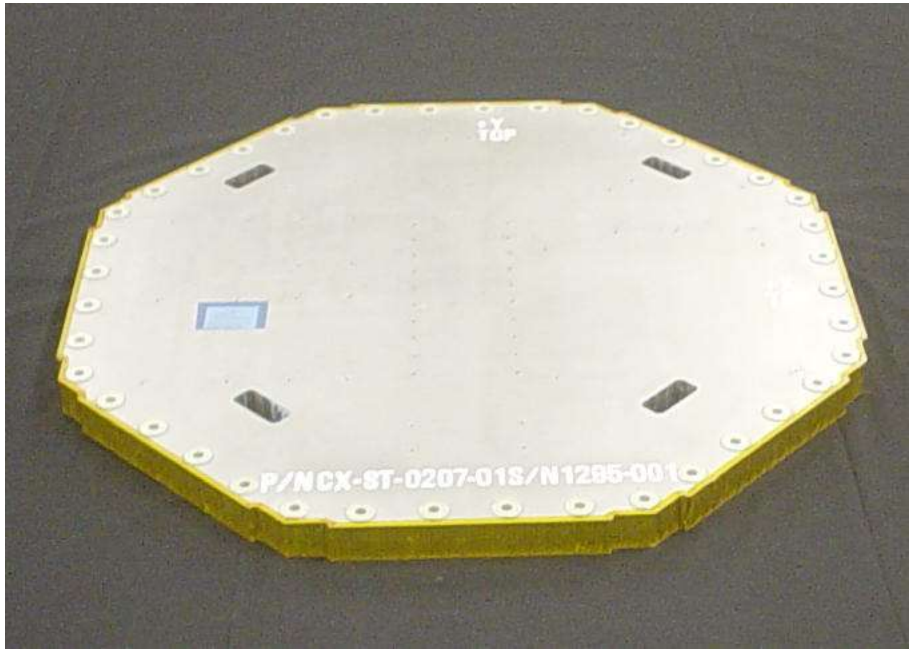


Heat Pipe Modeling – Takeaways

- Heat Pipes are not modeled in a high end CFD program, since such a model is very complicated, and would take a long time to run
- Instead, Heat Pipe Limits are calculated to determine the maximum power
- This power is combined with simplified models
- Simple Models using a high conduction core
- Assembly Modeling (heat pipe as thermal link in larger thermal systems)
  - ACT's classical method based on heat pipe solid cores with equivalent conductance
- Need to Verify Have Not Exceeded Max. Heat Pipe Power

CCHP Design

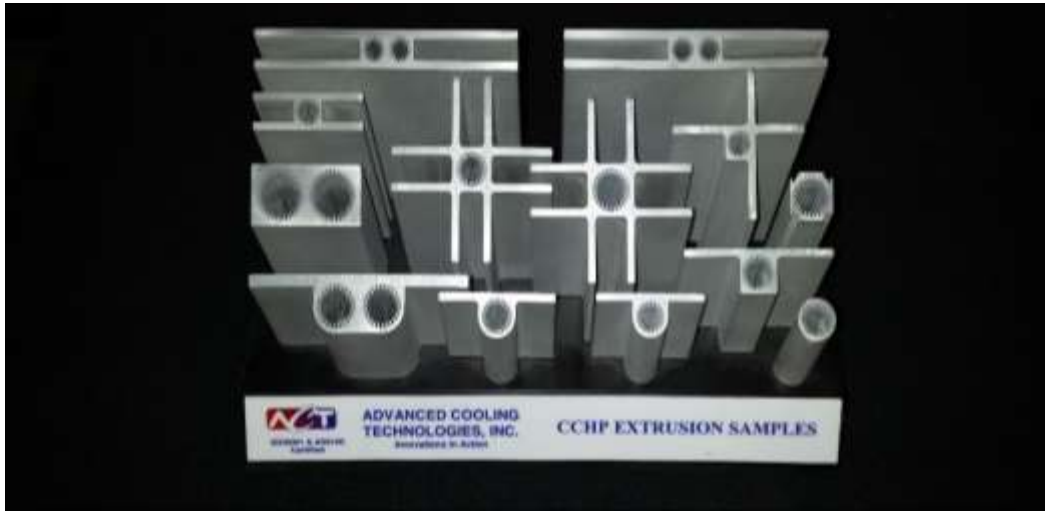
- Extrusions
- Saddles and Bending
- Effective Length and Transport Capability



Satellite Deck with Embedded Heat Pipes

Grooved Al/NH_3 Extrusion Selection

- Extrusion selection is based on three criteria:
  1. Transport Capability
  2. Redundancy
  3. Saddle Location
- Dual Bore used for higher transport capabilities or redundancy
- Integral saddles are desirable
  - Other option is soldered saddles
- Machine away saddles where not required
  - Can have multiple evaporators and condensers
- Depending on extrusion, Integral Saddles
  - Evap/Cond on the same side, opposite sides
  - Evap/Cond at 90°



CCHP Design - Saddles

- Extrusion must be machined before it can be bent
  - Remove flanges where bend, or not needed
- S-Bend heat pipes with multiple evaporators/condensers

Dual Bore Extrusions

- Dual Bore Extrusion can be bent both the hard and easy ways

CCHP Design

- ACT has an extrusion catalogue that presents current in-stock extrusions
- Geometry
  - Overall dimensions of the “as extruded” shape
  - Typical minimum machined cross section
  - Recommended minimum centerline bend radii for single bore heat pipes is 3.0 times the nominal extrusion cross section
  - Example: 375DFSQ, 0.375” x 3.0 = 1.125 “
- Thermal Performance
  - Transport capability 0.1 inch (typical ground testing performance)
  - Transport capability 0-g (on-orbit performance) is usually slightly greater
- Contact ACT for designs with multiple evaporators and/or condensers

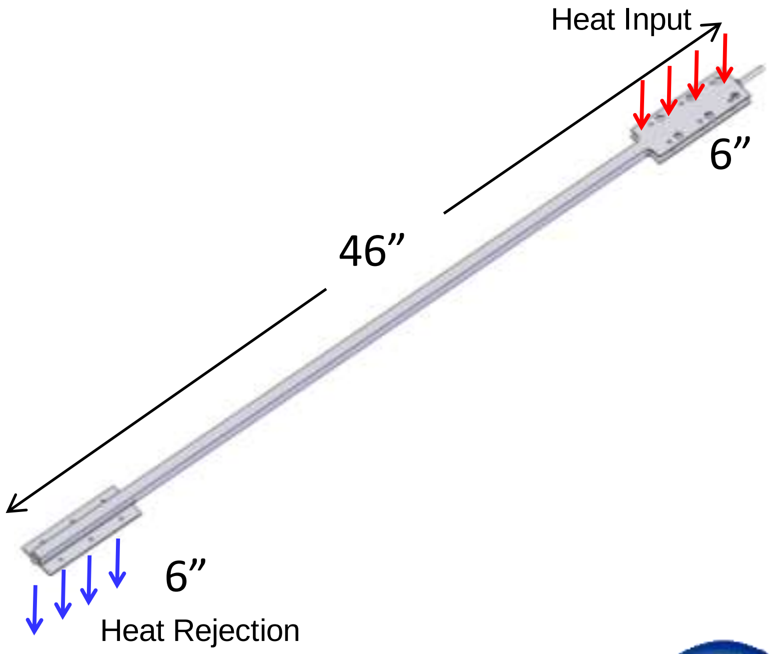
Heat Transport Determination

- Effective length is used to calculate the heat transport required for an aluminum ammonia constant conductance heat pipe (CCHP)

$$EffectiveLength = TotalLength - \frac{(EvaporatorLength + CondenserLength)}{2} - SlugLength$$

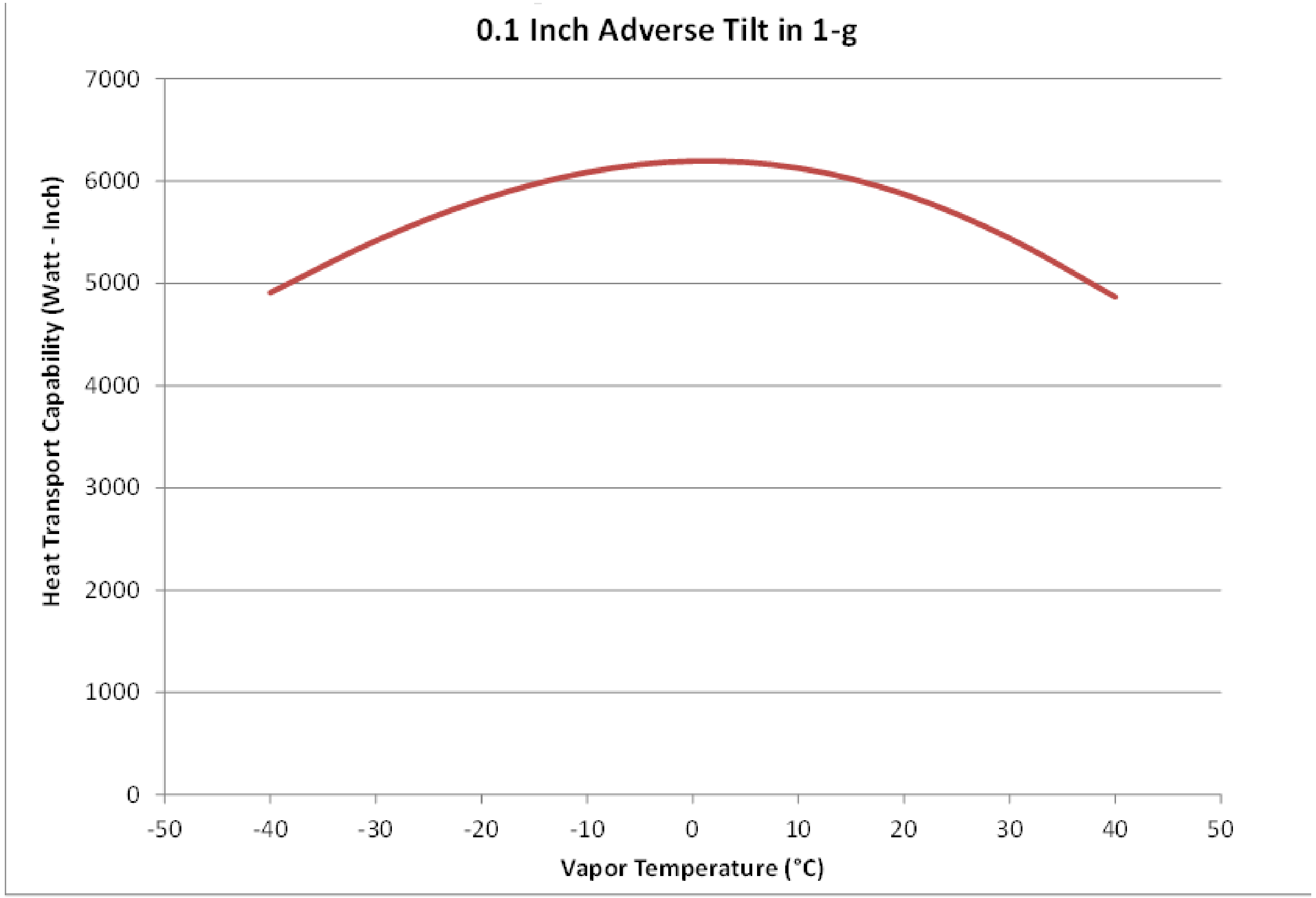
$$TransportRequirement = Q\max * EffectiveLength$$

  - Total Length: End to End overall length of axial vapor space
  - Evaporator Length: Axial length of evaporator interface
  - Condenser Length: Axial length of condenser interface
  - Slug Length: Length of liquid blockage at specific temperature
- Example
  - Total Length: 46 inches
  - Evaporator Length: 6 inches
  - Condenser Length: 6 inches
  - Slug Length: 0 inches
  - Qmax: 100 Watts
  - Transport Requirement: 4300 Watt-inches



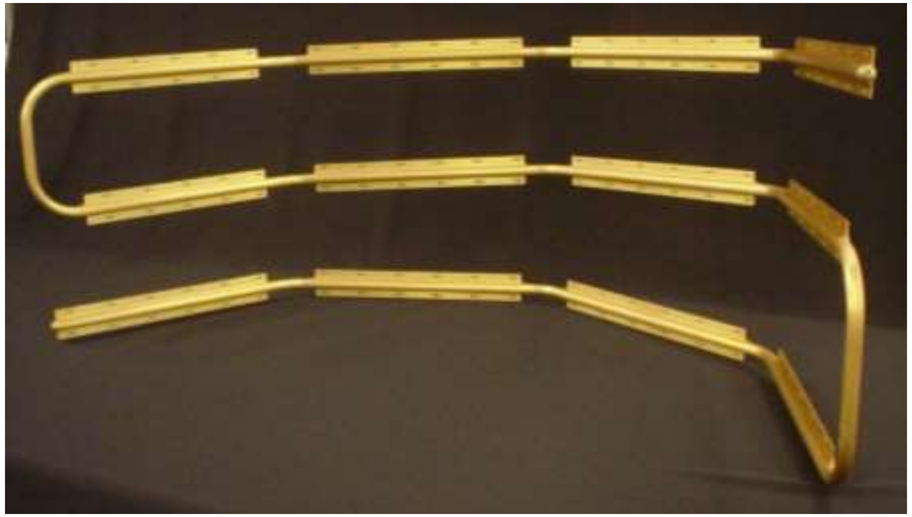
Typical Heat Transport Curve

- Underlying Assumptions: Neglect Gravity ΔP, Vapor ΔP



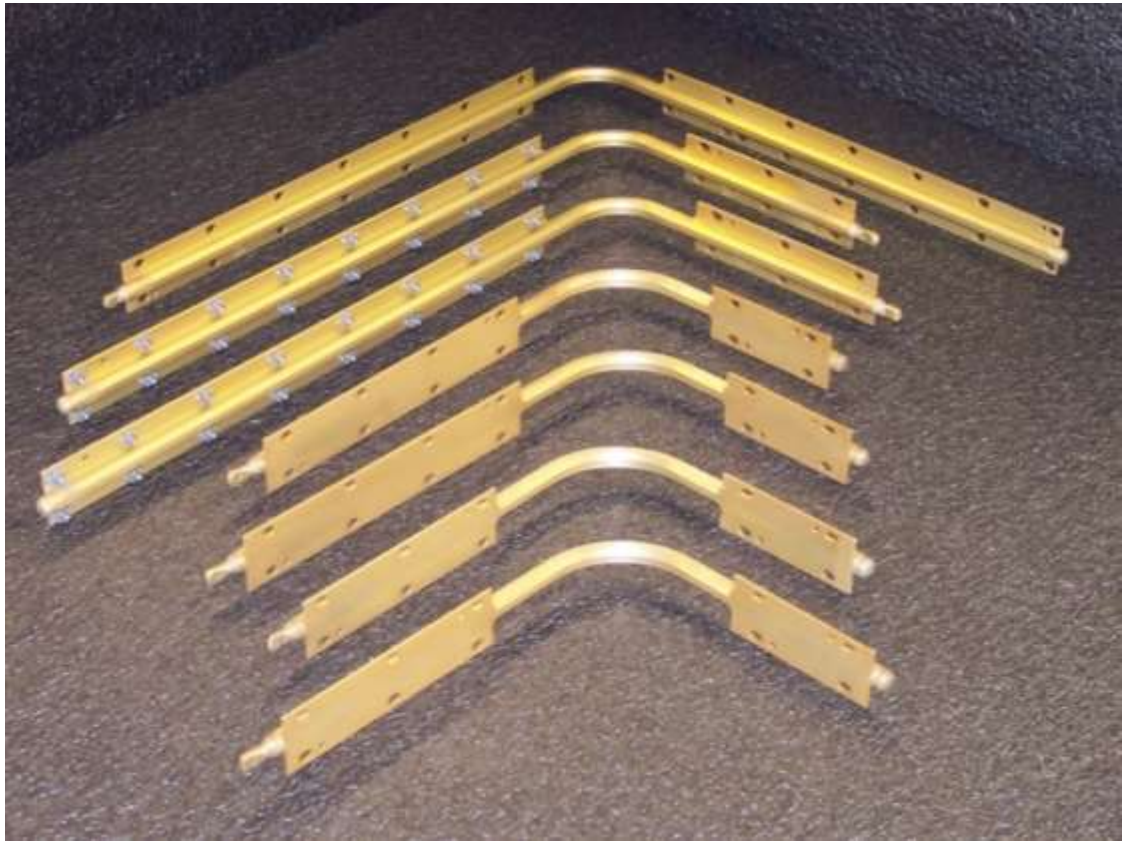
CCHP Design Takeaways

- Extrusion selection is based on three criteria:
  1. Transport Capability
  2. Redundancy
  3. Saddle Location
- Machine-away Flange Where Not Needed
  - Can also solder flanges
- Determine Transport Capability Required (W-in)
- Select an Extrusion with a Safety Factor



CCHP Manufacturing and Testing

- CCHP Manufacturing
- Heat Transport Verification
- Zero-g Performance Prediction
- Non-Condensable Gas Testing



Grooved Aluminum/Ammonia Heat Pipes

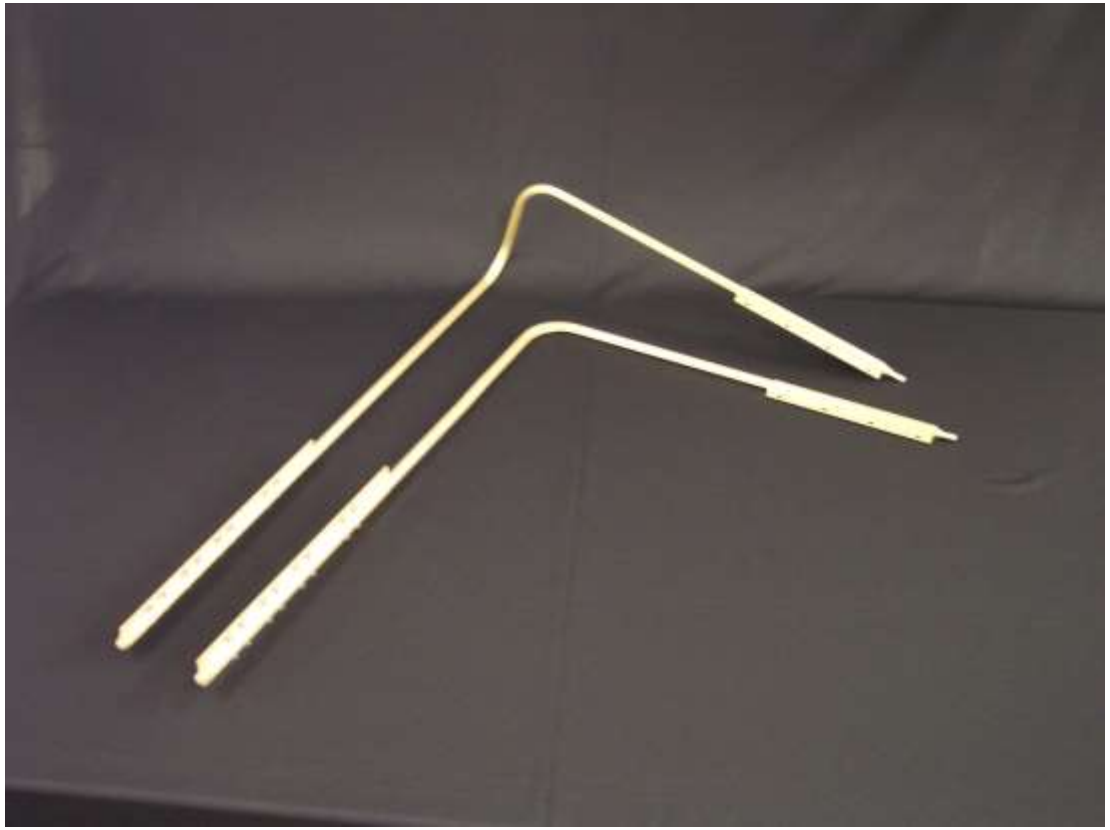
- In contrast to heat pipes on earth, CCHPs cannot be serviced once they are launched
  - Long life required, satellite will not operate properly without them
- Additional Steps are required to verify heat pipe operation
  - Inspections
    - X-ray all weld joints to prove low porosity in the weld
    - Dye-penetrant inspection
    - Ammonia leak checking with colorometric developer
  - Charging
    - Triple distilled ammonia
  - Testing
    - Test at cold temperatures to verify that there is no non-condensable gas
    - Typically -40, -50, -60°C

CCHP Heat Transport Verification Testing

- To verify operation, heat pipes are generally tested in an adverse elevation, where the evaporator is elevated above the condenser
  - Forces liquid to return through the wick
  - Avoids puddle flow in earth-based testing, where the liquid flows in a puddle on the bottom of the heat pipe
  - Puddle flow greatly overestimates heat pipe transport capability
- In contrast to terrestrial heat pipes, CCHPs have grooved wicks with a large pore size
  - Can only operate a short distance against gravity
  - Heat pipes normally tested with a 0.1 inch adverse elevation
    - 0.010 inch difference in elevation significantly affects the power
- Need to consider the heat pipe orientation during thermal vacuum testing
  - Normally orient so that the heat pipe is level or gravity aided during the thermal vacuum tests
  - If the tested assembly orientation would impose a heat pipe to work in unfavorable orientation, then the heat pipe will not work…so its functionality within the system would need to temporarily be replaced with a cooling loop.

CCHP Heat Transport Verification Testing

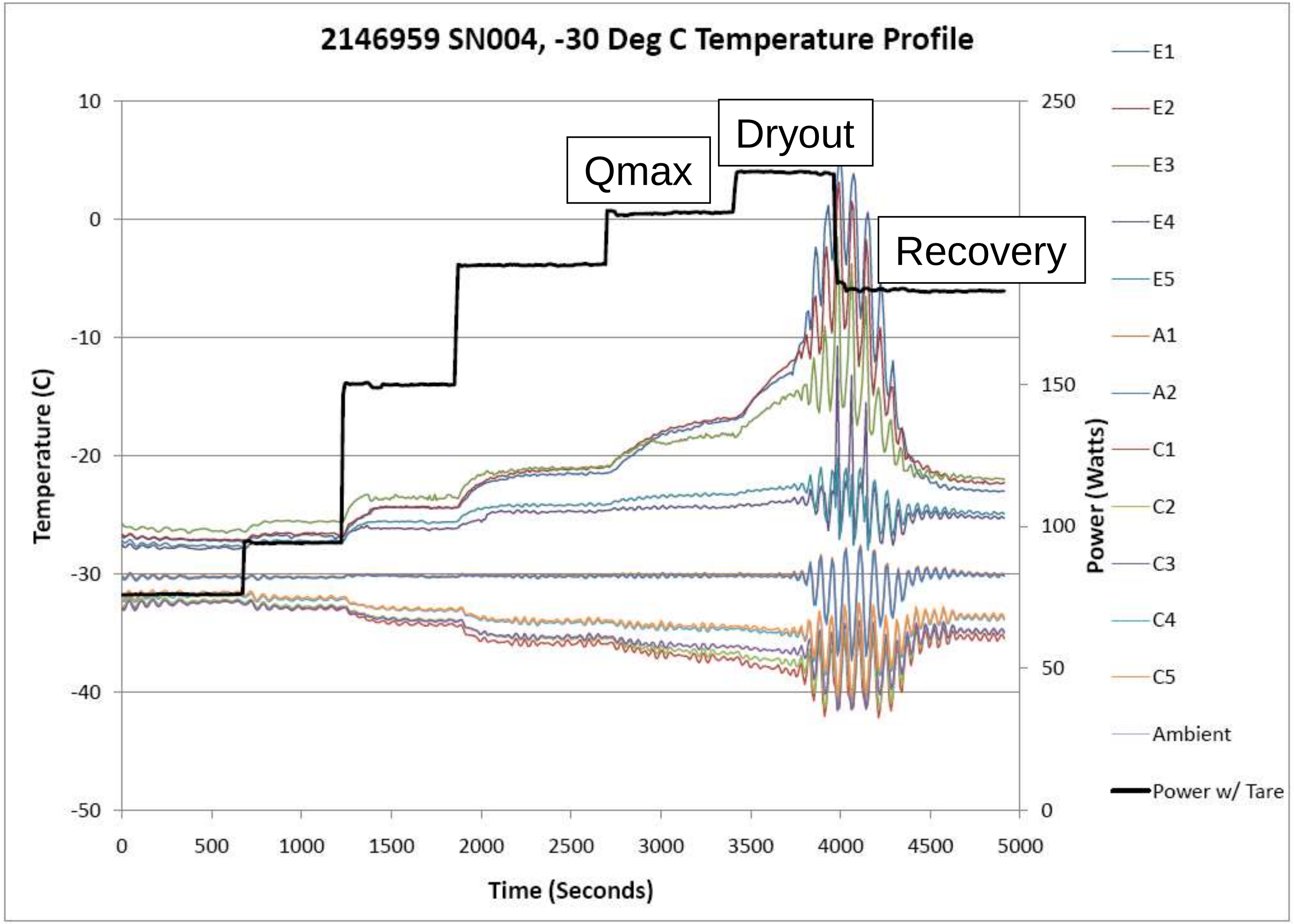
- Heat Pipe geometry is broken into two categories:
  - 2-D CCHPs
    - The path of the heat pipe is planar. The vapor core can be oriented such that there is no translation with or against gravity for 1-g testing (0.1 inch against)
  - 3-D CCHPs
    - The path of the heat pipe is complex. The vapor cannot be oriented such that there is no translation with or against gravity for 1-g testing



CCHP Heat Transport Verification Testing

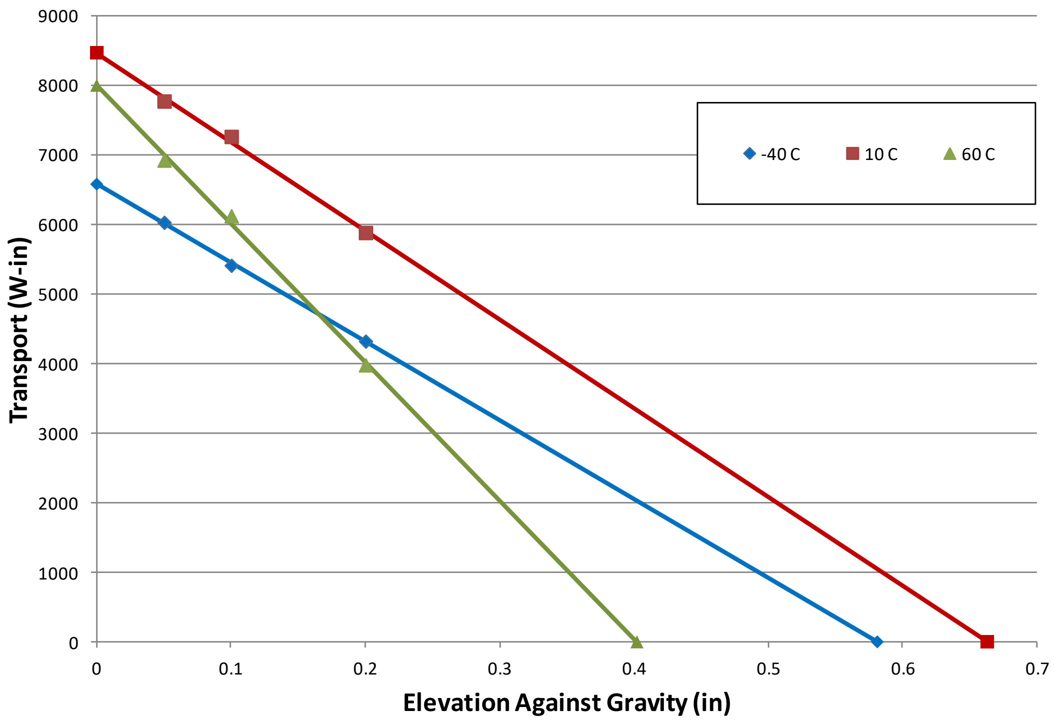
- The geometry of the heat pipe is essential in determining the degree to which the CCHP heat transport is verified
- 2-D CCHPs
  - To verify pumping performance of groove wick the heat pipe is oriented with the evaporator 0.1” above the condenser. This forces the wick to return liquid to the evaporator against gravity by capillary forces only.
- 3-D CCHPs
  - The heat pipe is oriented with the condenser above evaporator and operated with gravity returning liquid to evaporator. Wick does not function.
  - A 2-D equivalent heat pipe is built and tested at 0.1” adverse tilt.

CCHP Time Series Temperature Plot Example



CCHP 0-g Performance Prediction

- Performance in 0-g environment can be predicted using 1-g test data
- The CCHP can be tested at several adverse tilts to characterize the curve for Heat Transport vs. Adverse tilt.
- This curve can be extrapolated to predict 0-g transport capability

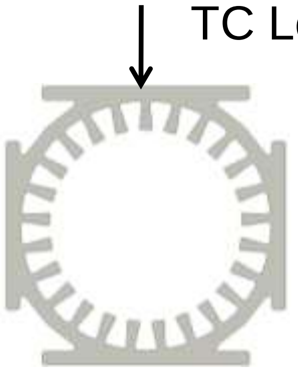


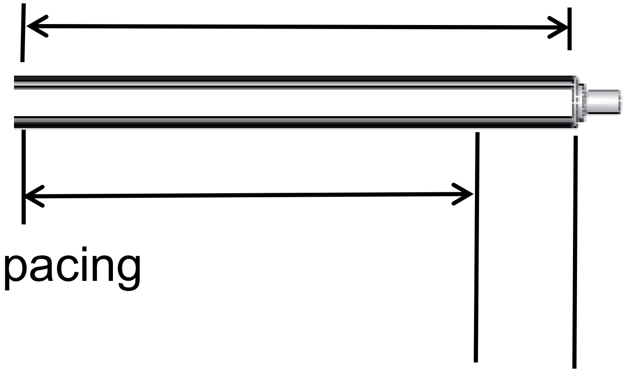
NCG Requirements for CCHPs

- CCHPs are installed on Satellites and are expected to operate for 15 to 20 years
- The accumulation of excessive NCG in the heat pipe blocks heat transfer to the heat sink and degrades performance
- Heat Pipes are used to cool critical systems for avionics, power distribution, communications, propulsion, and payload
- Customers specify maximum amount of NCG in one of two methods:
  - Length of NCG at -40°C, i.e. 0.5 inch at 0 day, 1.0 inch at 7 day
    - Reduced operating temperature allows NCG to occupy larger volume in the heat pipe (vapor pressure of ammonia at -40°C ~ 10 psi gage)
    - Days refers to time operating at elevated temperature (80°C to 90°C) after final pinch and weld
  - Pound Moles, i.e. 1×10^{-8} lb-moles at 0 day
    - Measure of number of atoms of NCG present
    - This can be verified at any temperature however testing is typically performed at -40°C to achieve desired resolution

NCG Measurement

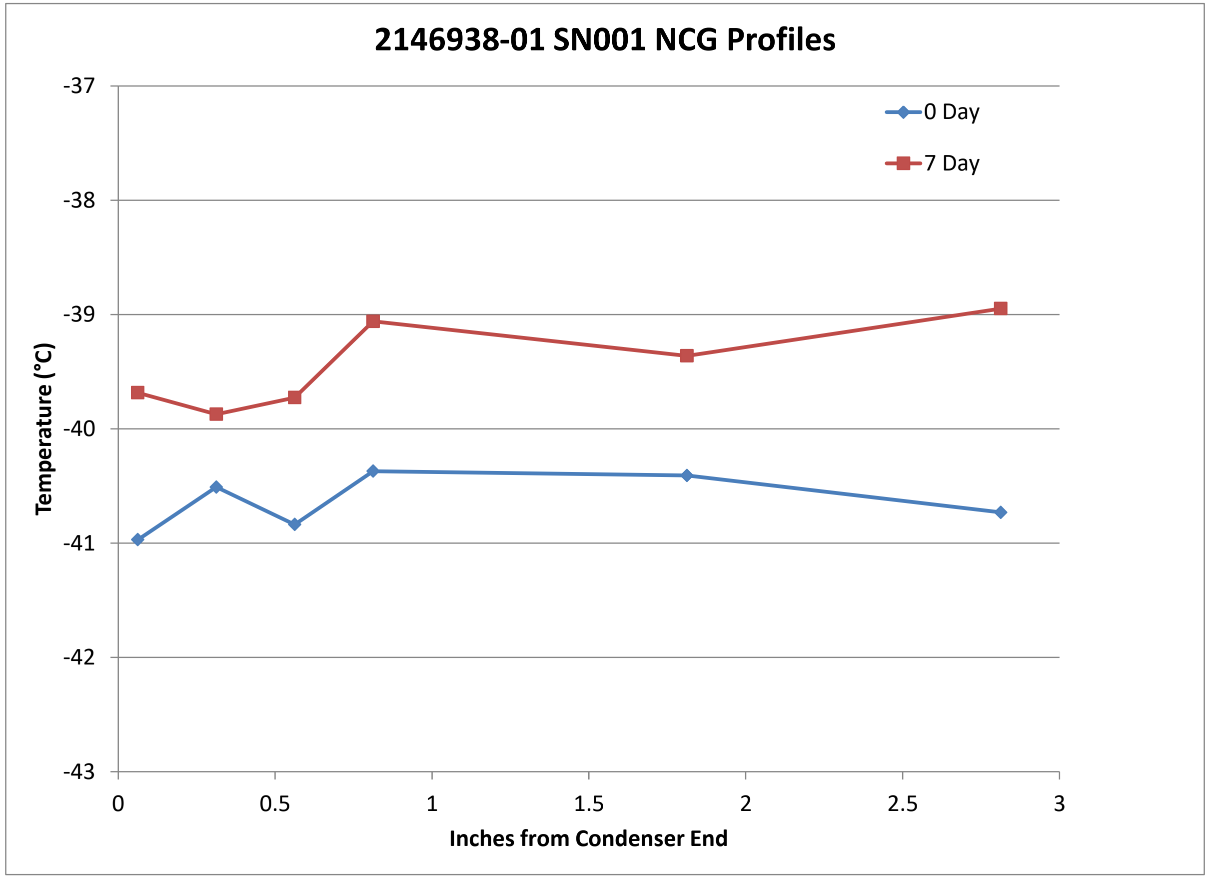
- The measurement of NCG is accomplished by measuring the thermal gradient across the condenser of the heat pipe.
- Heat Pipe is oriented gravity aided (min 0.25” condenser over evaporator)
- The heat pipe is chilled (bottom flange) to -40^{o}C (10 psi vapor pressure)
- 15 to 25 Watts is applied to the evaporator bottom flange
- Any NCG will collect at the condenser and block heat transfer to the chill block resulting in a decrease in temperature across the condenser





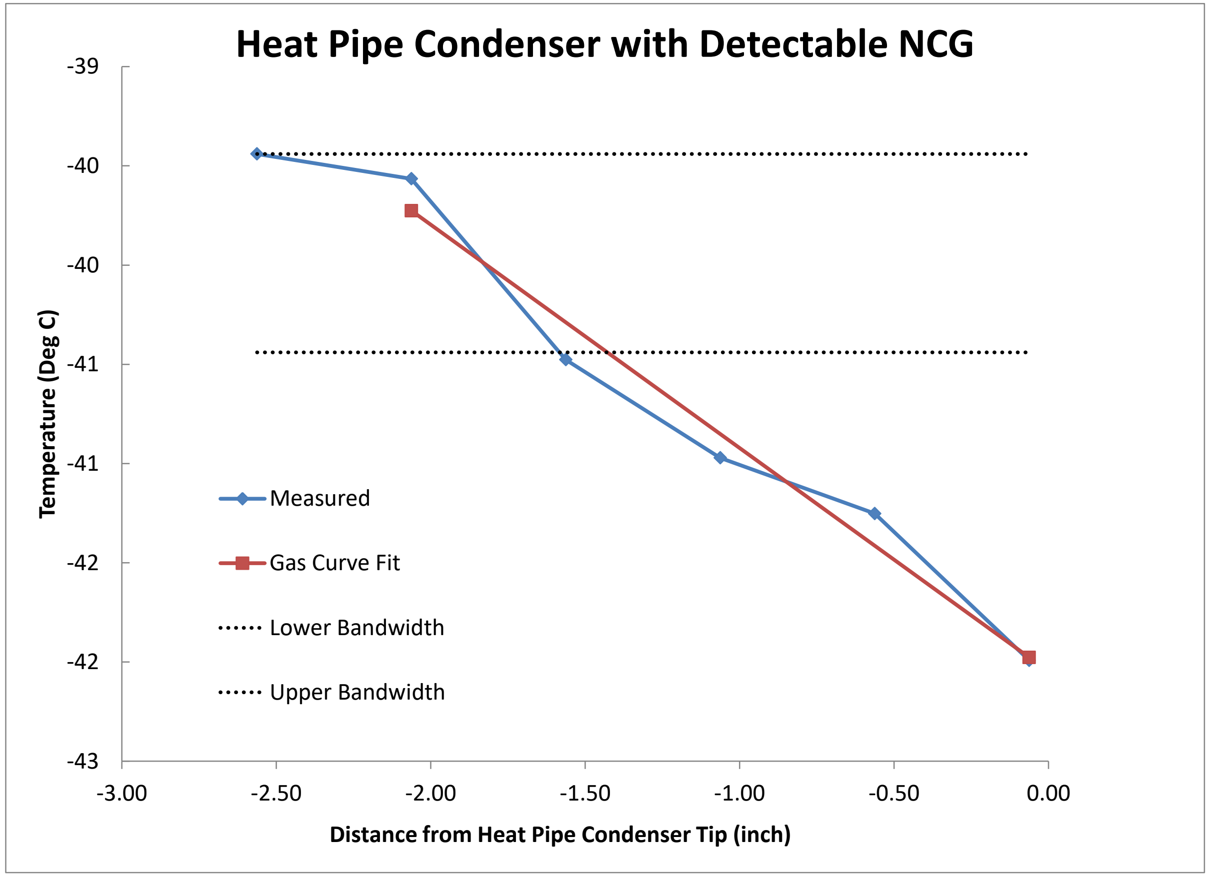
Example: No Detectable NCG

- A condenser that is isothermal within 1°C is considered to have "no detectable NCG"



Example: Detectable NCG

- A condenser profile falls outside the 1°C Bandwidth
- A line is fit to the data to determine the length of NCG



CCHP Heat Pipe Manufacturing Takeaways

- CCHPs are designed for long life
- Rigorous Manufacturing Proceeding, with Multiple Tests
- Conduct Thermal Transport Testing with heat pipe evaporator elevated 0.1 inch above the condenser
- Test at multiple elevations to extrapolate to zero gravity performance
- Test NCG amounts before sealing and shipping

VCHPs for Variable Thermal Links

- VCHPs can also be used for variable thermal links
  - Maintain evaporator temperature range in a fairly broad temperature range with large variations in sink temperature
  - Transmit heat readily during hot sink conditions
  - Minimize heat transmission during cold sink conditions
- Variable Thermal Link useful when
  - Variable system loads resulting from intermittent use
  - Large changes in environment temperature
    - Lunar surface temperature range: -140 °C to 120 °C
  - Limited electrical power
    - Lunar Application: 1 W = 5 kg of energy storage and generation
- Applications that can benefit from using VCHPs as variable thermal links include
  - Lunar and Martian Landers and Rovers
  - Research Balloons (fly near Poles in winter)
  - Lunar and Space Fission Reactors

VCHP Reservoir Location and Connections

- Generally want the NCG to fill the condenser and adiabatic sections when shut down
- Variable thermal link VCHPs can have 3 different reservoir configurations

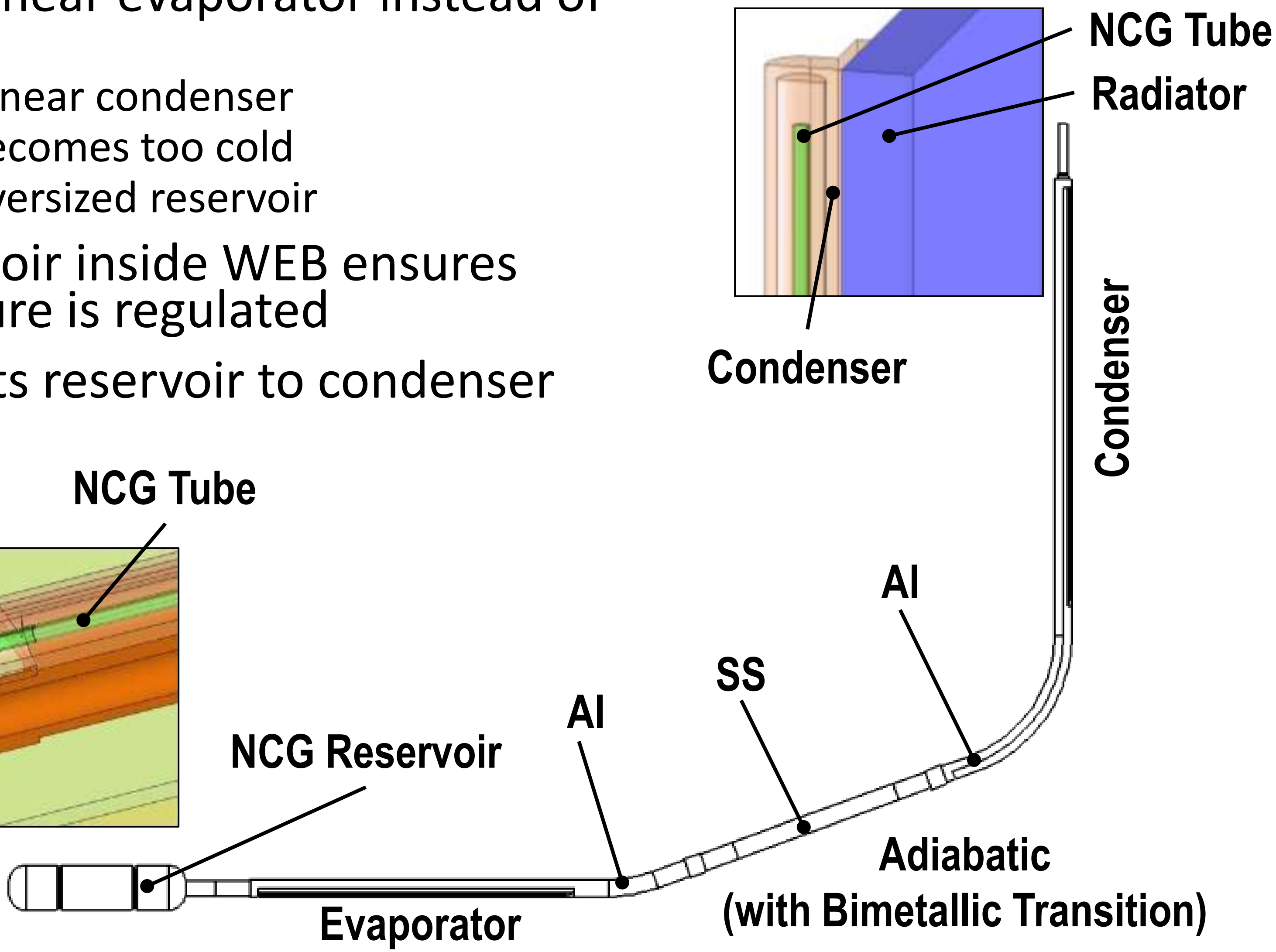
1. Reservoir located near the evaporator, with an internal line
   - Warm reservoir, tighter temperature control
   - More expensive to fabricate, may aid in routing
2. Reservoir located near the evaporator, with an external line
   - Warm reservoir, tighter temperature control
3. Reservoir at the end of the condenser
   - Conventional geometry , easiest and cheapest to fabricate
   - Cold reservoir, sets a minimum allowable ΔT

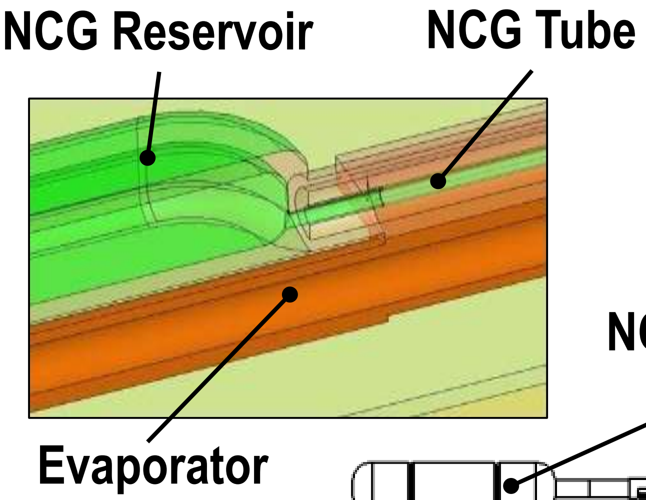
Variable Thermal Links for the Moon & Mars

- Warm reservoir VCHPs are useful for the Moon and Mars, since they don't require any electrical power to control the temperature
- The Lunar night is 14 days long in most locations
- 1 W Power = 5 kg Batteries!
  - Extremely important to minimize power usage at night
- 14° Gravity Adverse Tilt for Landers, up to 45° for Rovers
  - Conventional grooved aluminum/ammonia CCHP not sufficient
  - Hybrid wick: screen/sintered in evaporator, grooved adiabatic/condenser
  - 96 K Minimum Sink Temperature (Lunar Night)
    - Thermal link will experience very cold temperatures
    - Ammonia will freeze
  - Must keep batteries and electronics warm

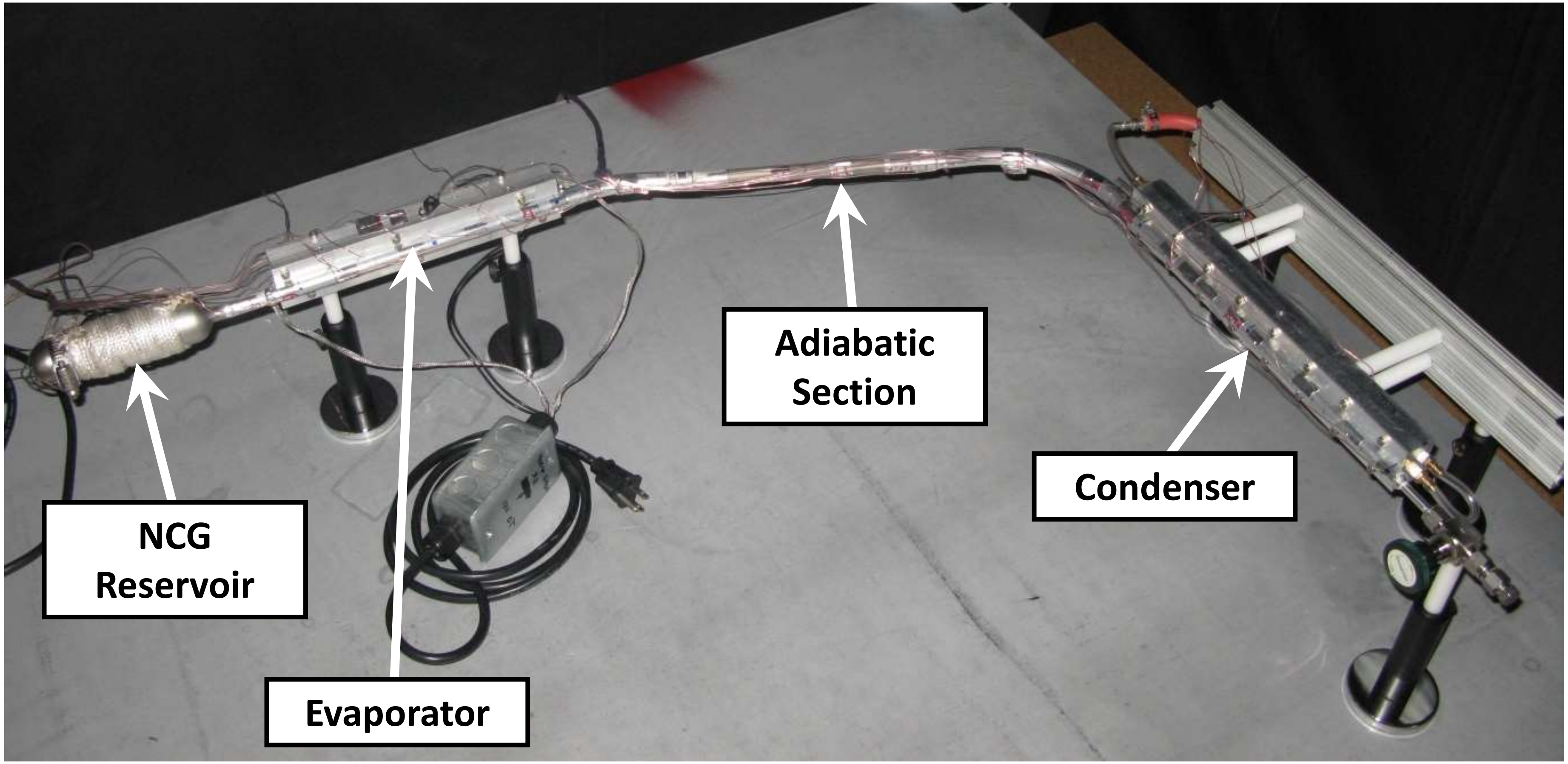
VCHP Design – NCG Reservoir near Evaporator

- Reservoir located near evaporator instead of condenser
  - Normally placed near condenser
  - ILN condenser becomes too cold
  - Would require oversized reservoir
- Location of reservoir inside WEB ensures that its temperature is regulated
- NCG tube connects reservoir to condenser

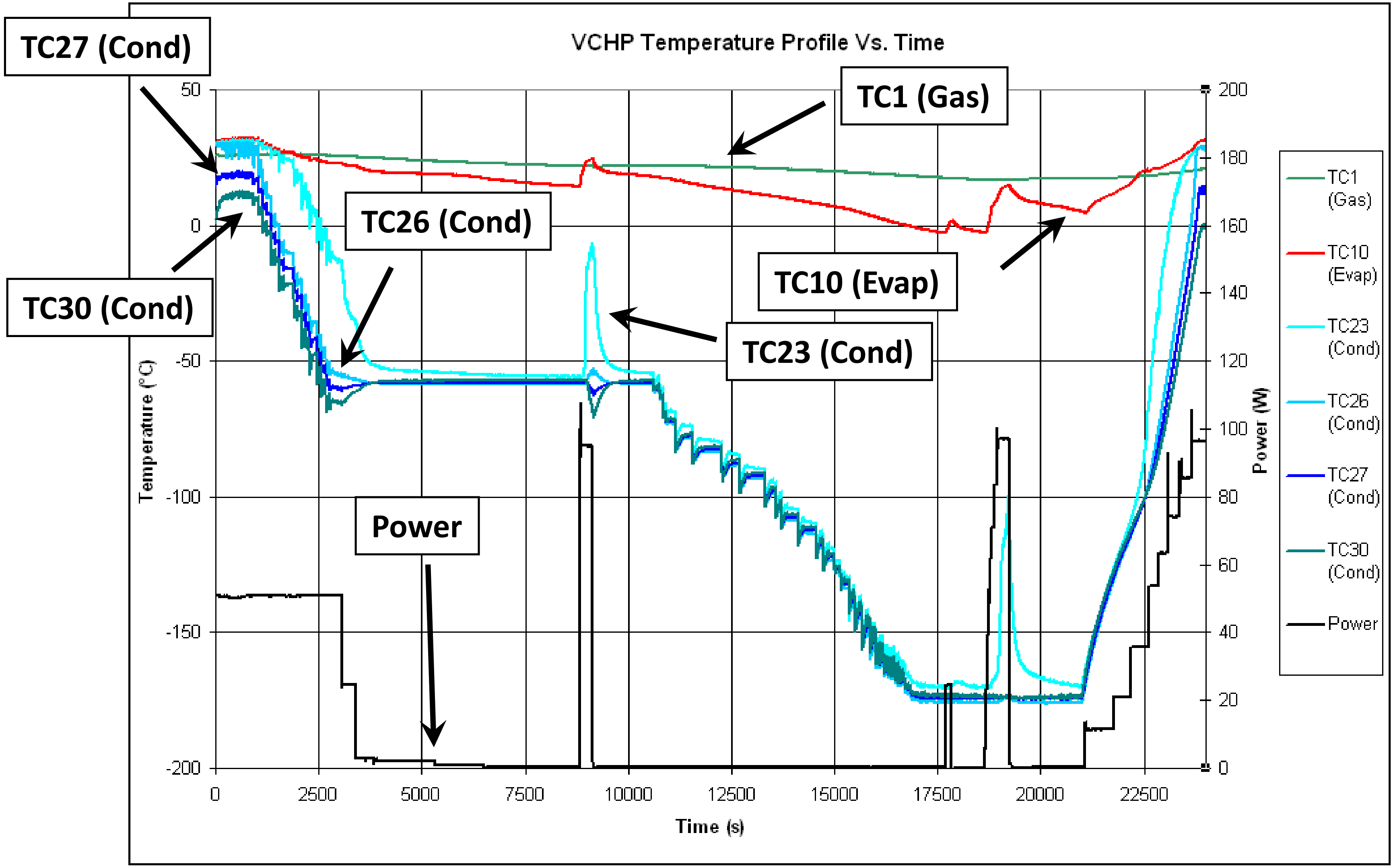




Warm Reservoir VCHP

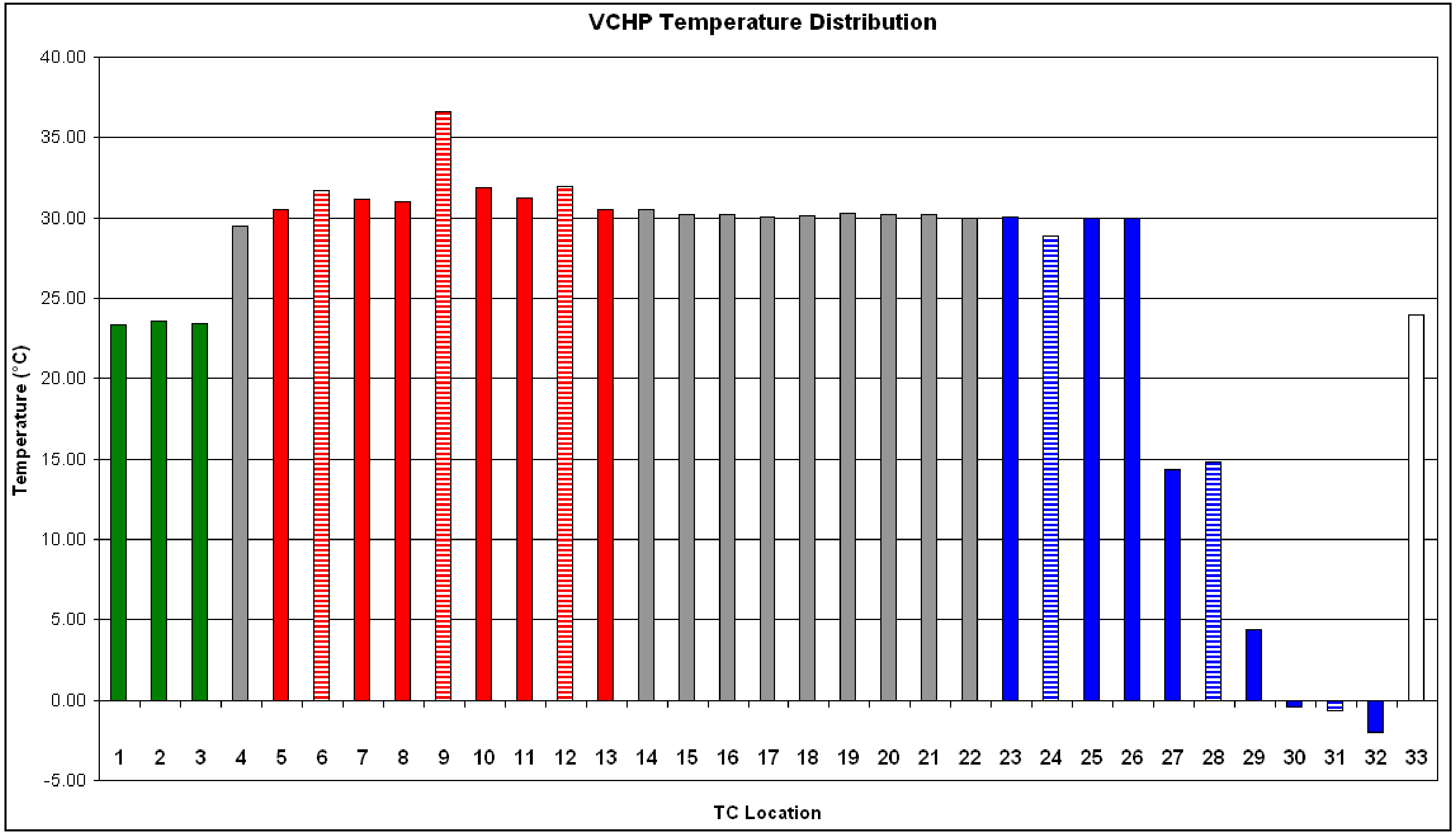


VCHP Testing – Lunar Freeze/Thaw Results



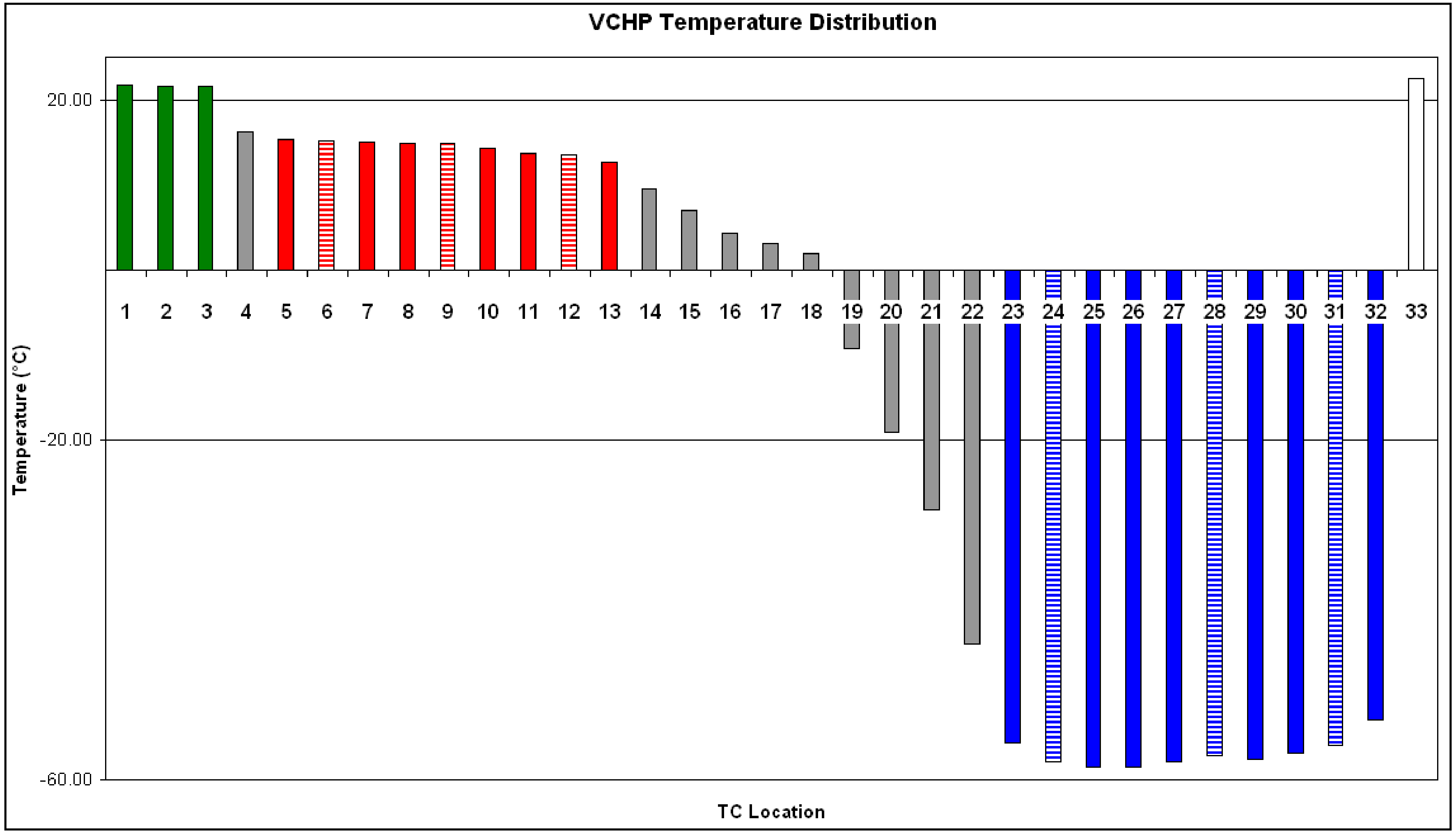
VCHP Testing – Lunar Freeze/Thaw Results

VCHP Operation (25 °C, 95 W, -2.3°)



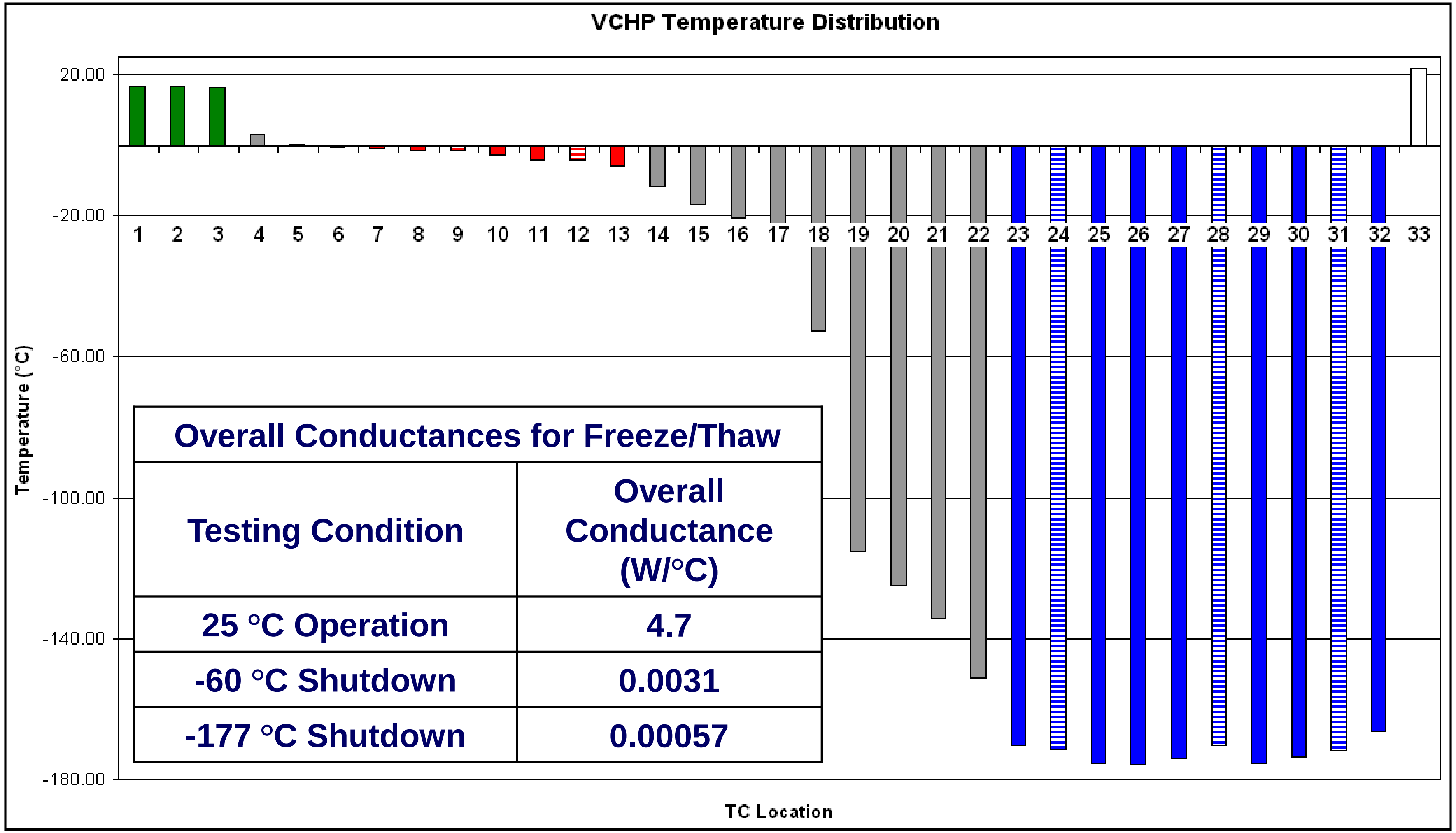
VCHP Testing – Lunar Freeze/Thaw Results

VCHP Cold Shutdown (-60 °C, 0.2 W, -2.3°)



VCHP Testing – Lunar Freeze/Thaw Results

VCHP Very Cold Shutdown (-177 °C, 0.1 W, -2.3°)



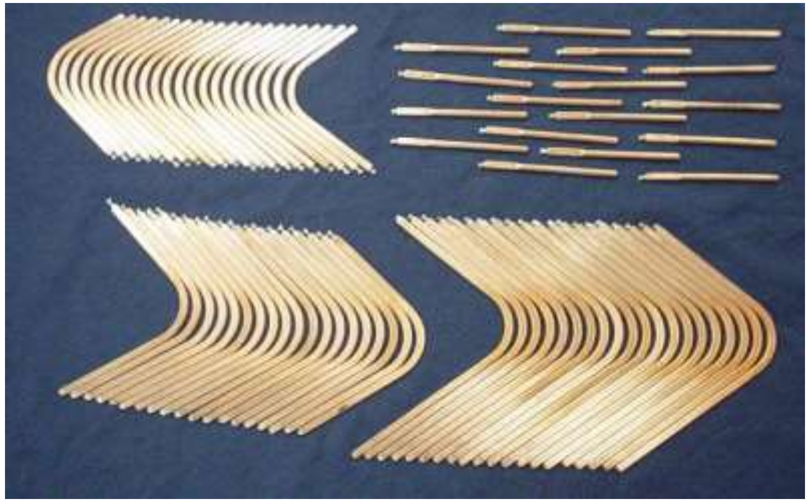
Overall Conductances for Freeze/Thaw	
Testing Condition	Overall Conductance (W/°C)
25 °C Operation	4.7
-60 °C Shutdown	0.0031
-177 °C Shutdown	0.00057

VCHPs for Variable Thermal Links Takeaways

- Applications that can benefit from using VCHPs as variable thermal links include
  - Lunar and Martian Landers and Rovers
  - Research Balloons (fly near Poles in winter)
  - Lunar and Space Fission Reactors
- Both Cold Reservoir and Warm Reservoir VCHPs can be used as variable thermal links for Lunar and Martian landers and rovers
- Cold reservoirs have very loose thermal control, and a minimum ΔT band
- Warm reservoir VCHPs can passively maintain temperatures within a few °C over wide swings in power and sink conditions

Copper/Water Heat Pipe Design

- Design Inputs
- Water Heat Pipe Limitations
- Operating/Storage Temperatures



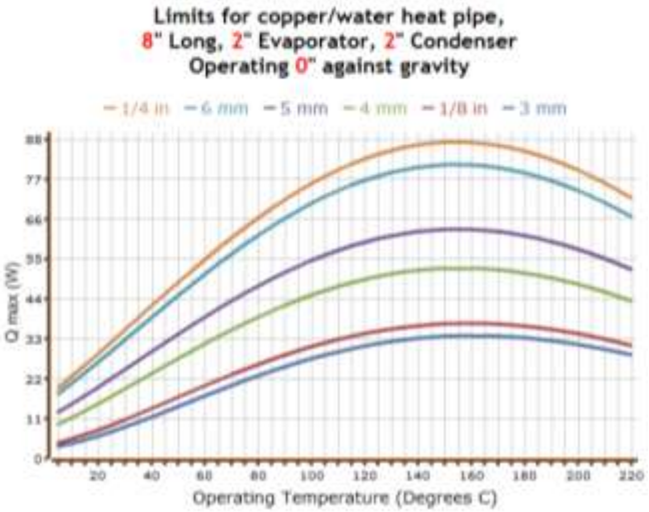
Copper/Water Heat Pipe Design Inputs

- Length, Orientation, Acceleration
  - Sets maximum hydrostatic force
  - Determines allowable wick designs
- Will the heat pipe always be gravity aided?
  - Gravity aided systems can use thermosyphons
  - Longer distances
  - Higher powers
- Bends, other constraints
- Temperatures
  - Operating
  - Storage

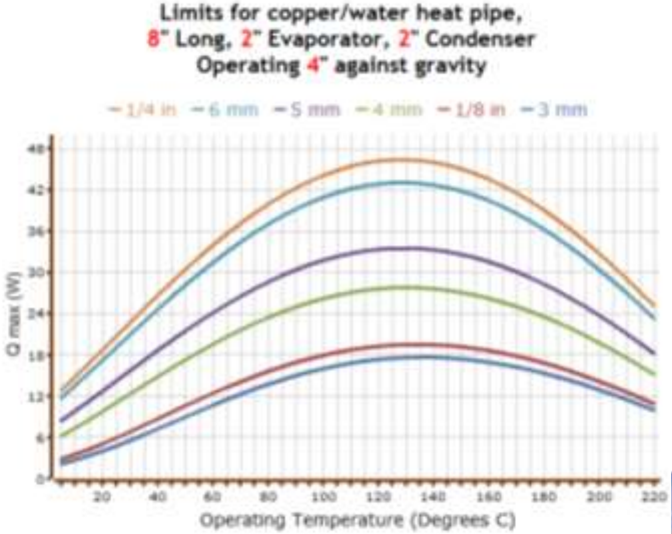
Two Phase Water Performance Limits

- Three General Limitations for water heat pipes, HiK™ plates, and vapor chambers
  - Temperature
  - Vertical Height
- Water is the best and most common working fluid
  - Can be an effective working fluid from approximately 25°C to 280°C
  - Below 25°C ability to transfer power drops off
  - Heat transfer by conduction only below 0°C, when water freezes
    - Normally not an issue with electronics cooling
    - Note that properly designed heat pipes can withstand thousands of freeze/thaw cycles
- Water heat pipes can operate with the evaporator elevated a maximum of 9-10 inches (23-25 cm) above the condenser

Horizontal

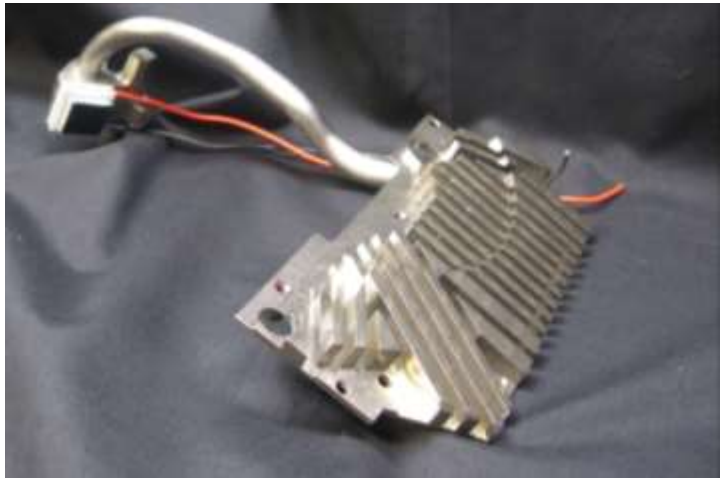


4" Against Gravity



Copper Heat Pipe Design Constraints

- Heat Pipe Routing
  - Standard Pipe Sizes:
    - 3,4,5,6,8 mm
    - 1/8, ¼, 3/8, ½ in
  - Bending ~ 3x OD
  - Flattening ~ 2/3 OD
- Integration
  - Grooves or blind hole
  - Epoxy
  - Solder

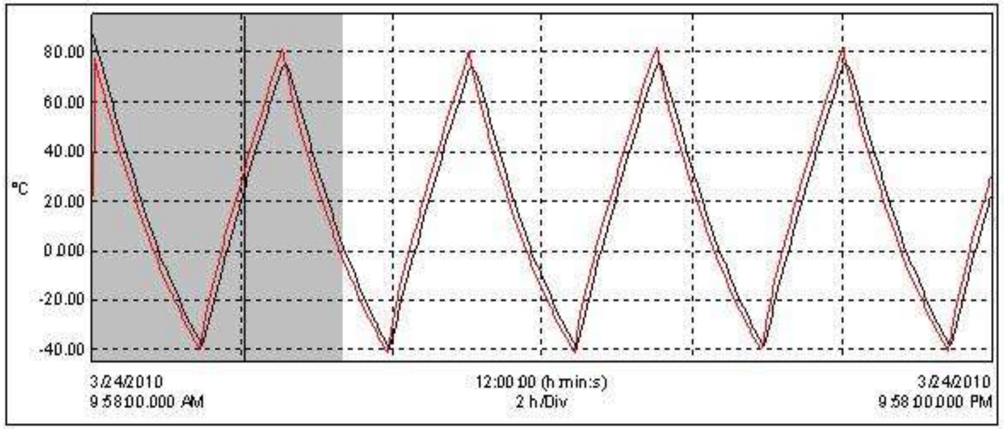


Copper/Water Heat Pipe Temperatures

- Heat Pipes can be designed to operate over the most demanding temperature extremes
  - Operational: -55°C to +85°C, depending upon requirements
  - Survival: -55°C to +125°C , depending upon requirements
- Lower Temperature Range
  - Below 0°C, heat transfer with a copper/water heat pipe is mostly conduction
    - Thermal management using heat pipes are not typically needed
    - Heat pipes start to operate as the electronics box temperature increases above the freezing point.
- Upper Temperature Range
  - Above 100°C, the vapor pressure of water is higher than ambient.
  - 105°C is the maximum operational/survival temperature for most copper/water vapor chambers, 150°C for specialized systems

Copper/Water Heat Pipe Thermal Cycling

- In properly made heat pipes, the working fluid fully saturates the wick without making a puddle of excess fluid
  - Fluid completely contained within the wick
  - Not able to bridge the gap across the inside diameter of the heat pipe
  - Allows multiple freeze thaw cycles to occur without heat pipe deformation.
- Typical freeze thaw tests at ACT
  - -20°C to +20°C and -45°C to +125°C.
  - Up to 1,200 cycles
  - Thermal cycle both heat pipes and their assemblies including Hi-K plates



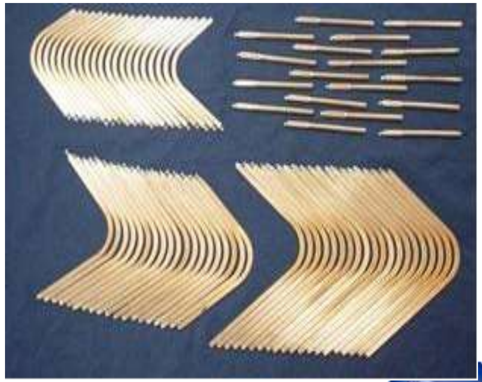
Freeze/thaw cycle data

Copper-Water Heat Pipe Design Takeaways

- Operate from roughly 25° to 150°C
  - Titanium/Water and Monel/Water to 250°C
  - Operate up to 10 in. (25 cm) against gravity
- Freeze/Thaw Tolerant
- Copper/Water heat pipes and HiK™ plates used in ground and spacecraft electronics boxes
- Copper/Water vapor chambers used for isothermalization, and for very high heat fluxes (up to 1,000 W/cm^2)

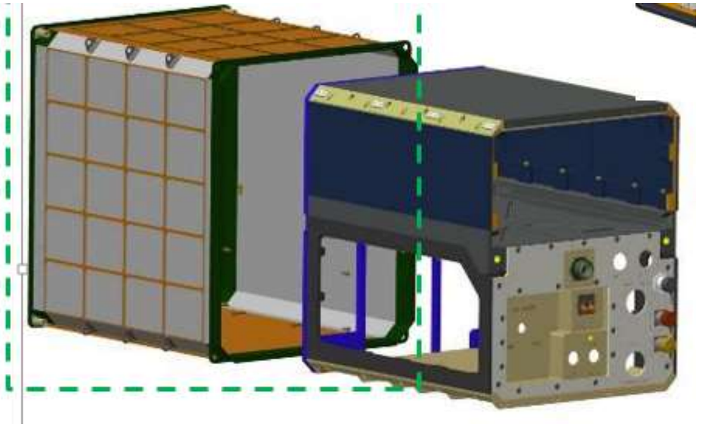
Copper/Water Heat Pipes in Space

- Motivation/Benefits
  - Operate at temperatures up to 150°C, versus 80°C for aluminum/ammonia heat pipes
  - Can be incorporated into electronics assembles and reduce peak temperature or increase power
  - Ground testable up to 25 cm
- Qualification / Space Readiness
  - TRL 9 – ACT First Launch in April 2019
  - Freeze/Thaw Tolerant
  - Shock Vibration Tolerant
  - Mil-Std 810-g typically performed at assembly level
  - No moving parts
- Titanium/water heat pipes and radiators available at temperatures up to 250°C
  - Can be used for higher temperature radiators, reducing mass and size



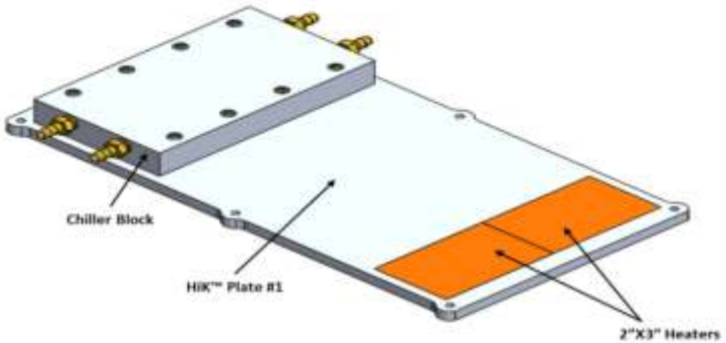
The Advanced Passive Thermal eXperiment (APTx) on board the ISS

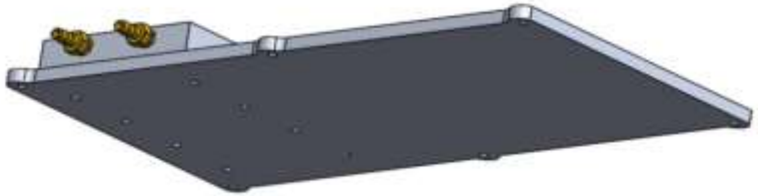
- NASA Marshall and NASA Johnson worked on an ISS flight experiment with components supplied by ACT.
- The ISS test rack has a lower and an upper section.
  - The lower section has the PCHX fluid loop from a previous PCM module test.
  - PCHX loop was on the ISS, with duplicate loop on ground
  - Swap lockers for different Experiments
- Experimental Configuration
  - ACT's Aluminum HiK™ plates with embedded copper/water heat pipes

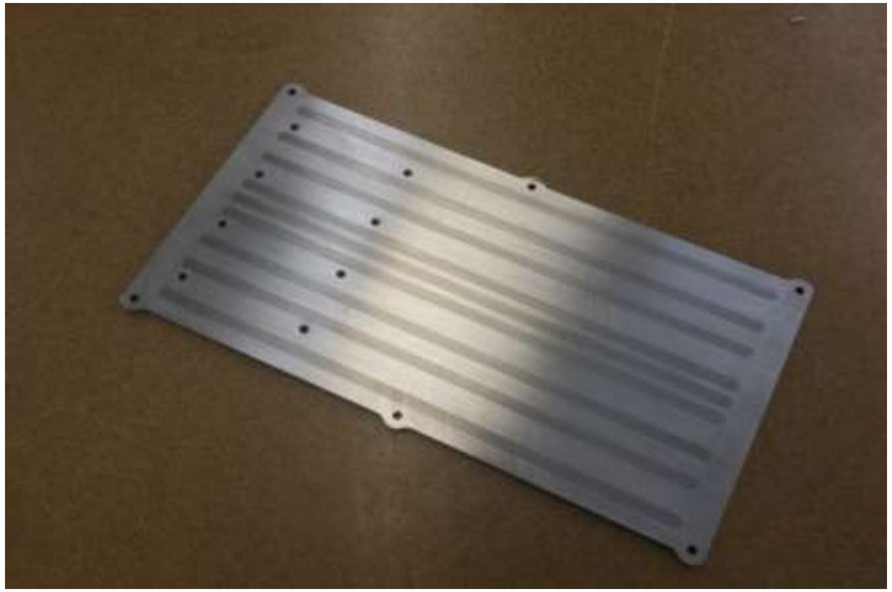


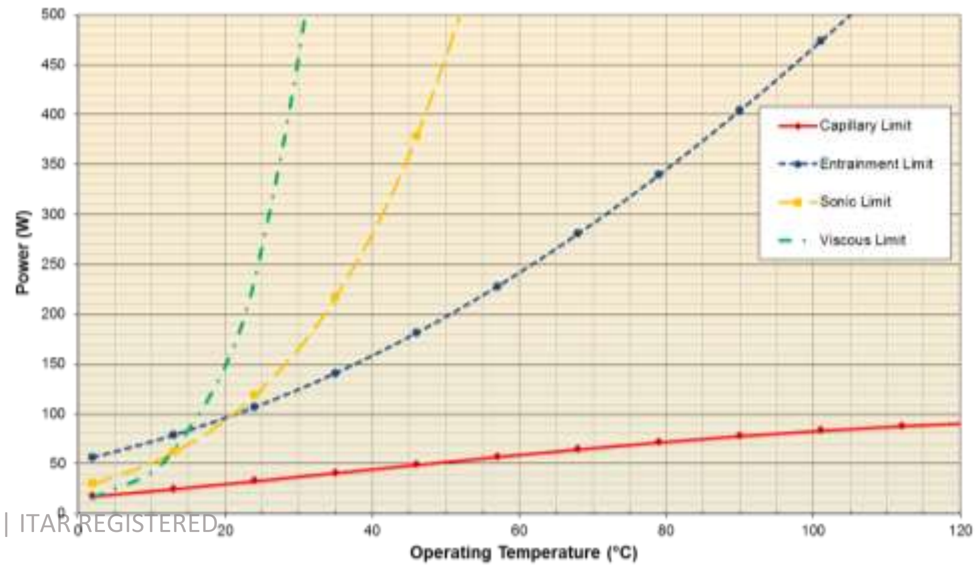
HiK™ Plate – Ground Testing

- Two 53W (2”x3”) silicon heaters were used as a heat source on the top of the HiK™ plate;
- A chiller block was used to impose sink temperatures between -10 to 40°C
- Freeze/thaw testing was performed for the HiK™ plate on the ISS.
- Each HiK™ plate had 9 copper/water heat pipes, 0.25 in. diameter, 11 in. long. Each heat pipe can carry up to 65 W at 70 °C before dryout due to the capillary limit



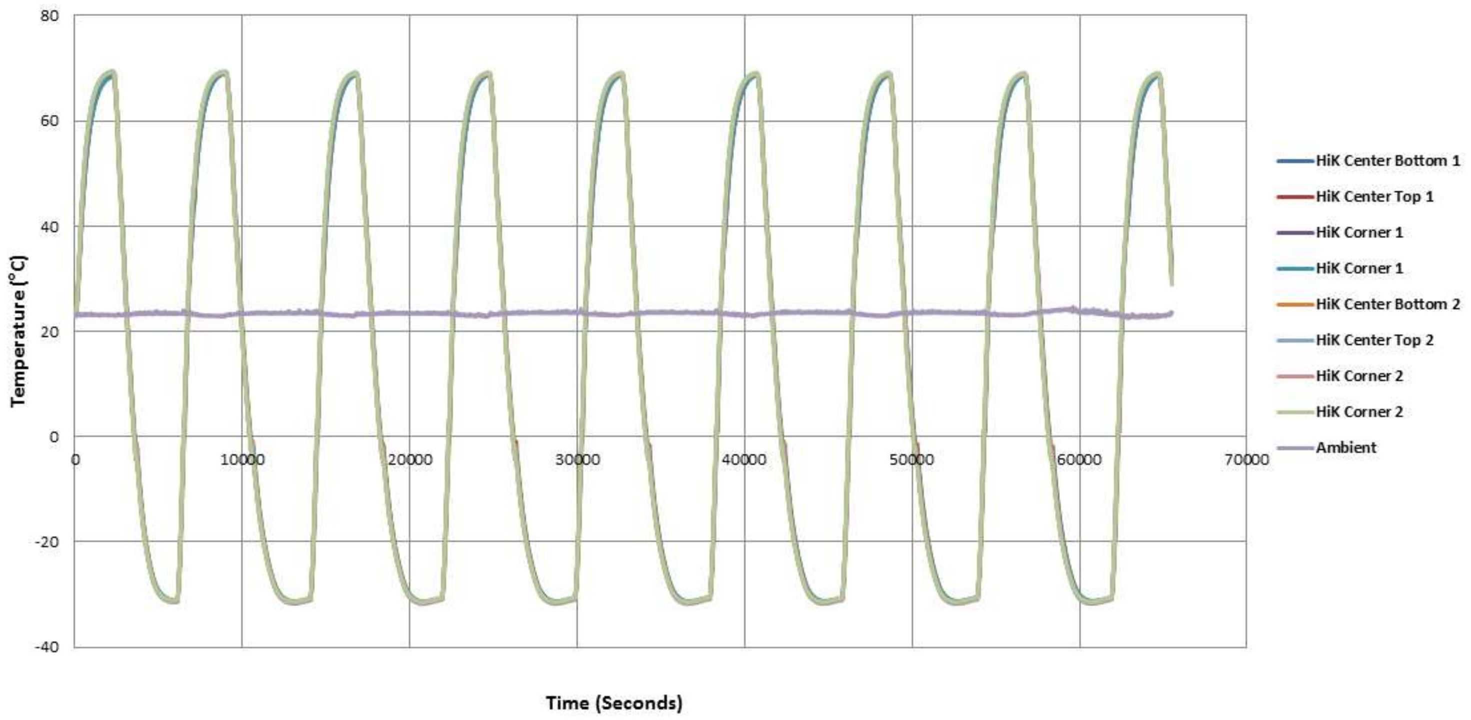






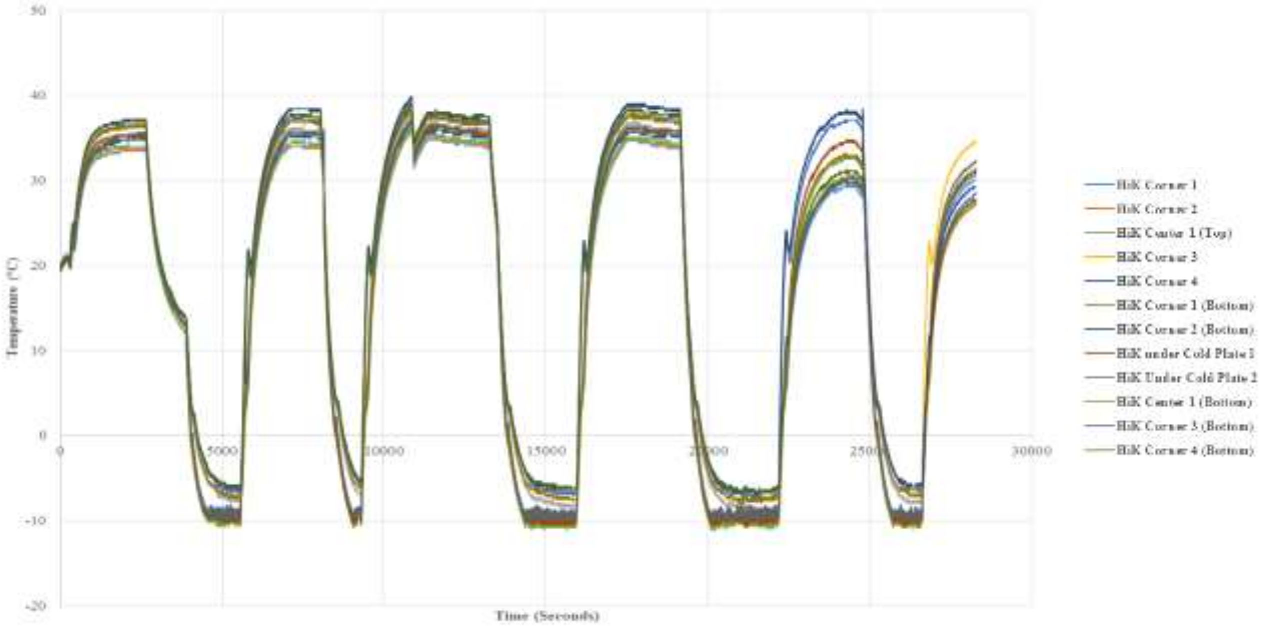
Ground Freeze/Thaw Cycle for HiK™ Plates

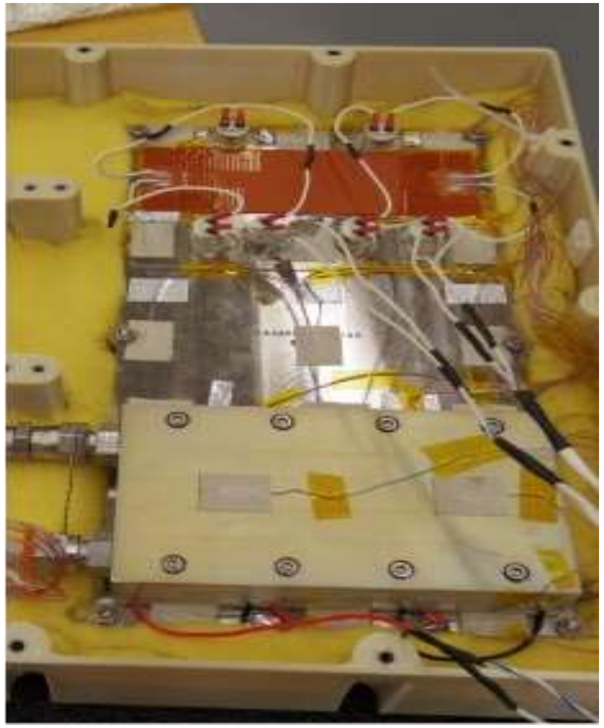
- Freeze thaw tests were conducted from temperature ranging from -30 to +70°C for two of the HiK™ plates.
- The plates were subjected to 15 freeze/thaw cycles.
- The embedded copper/water heat pipes can sustain these freeze/thaw cycles without damage.



Microgravity Testing on the ISS

- Freeze/thaw testing was performed successfully for the HiK™ plate on orbit.
- The freeze/thaw tests were conducted for the HiK™ plate from temperature ranging from -10°C to approximately 40°C.
- Fourteen cycles of freeze-thaw and freeze-startup-thaw cycles were performed on orbit.



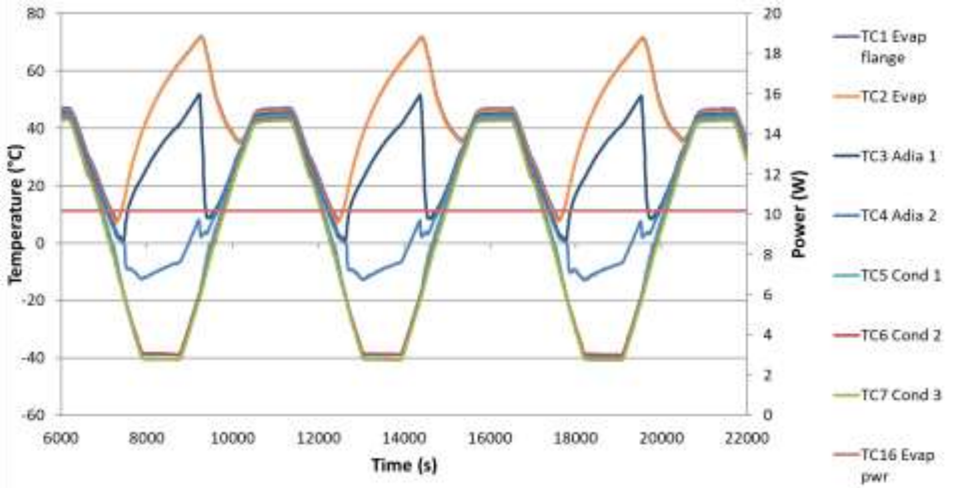


The assembled HiK™ plate integrated in Payload 2

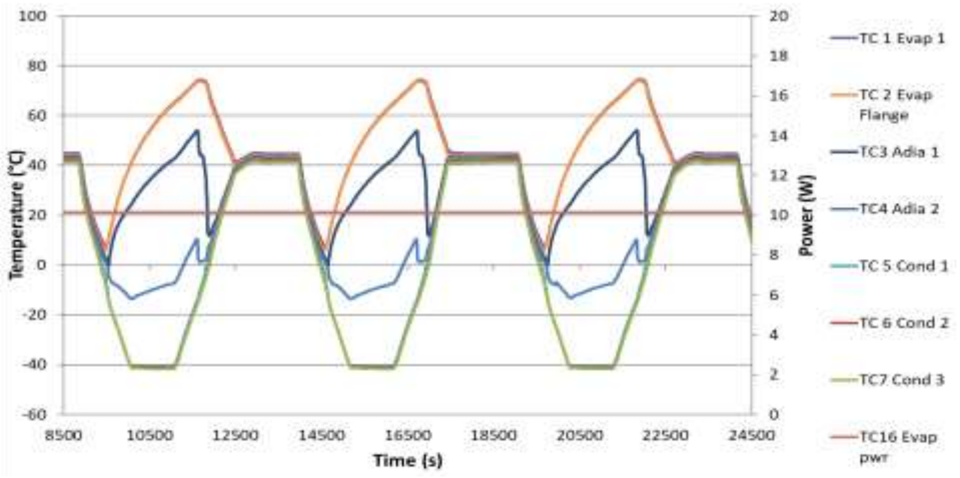
Copper-Water Heat Pipes – Additional Validation

- Survival of >1000 powered freeze-thaw cycles with constant thermal response and no dimensional deformation
- Consistent ability to start from frozen condition
- Shock & Vibe tolerance

Powered Freeze-Thaw Life Testing



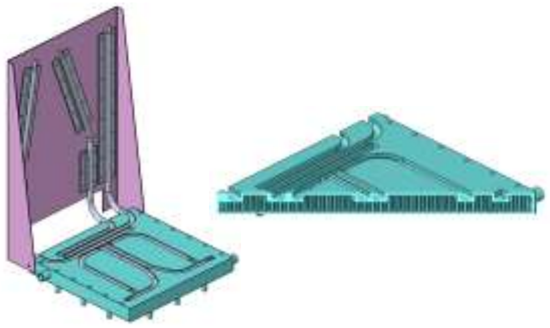
Response at ~50 cycles

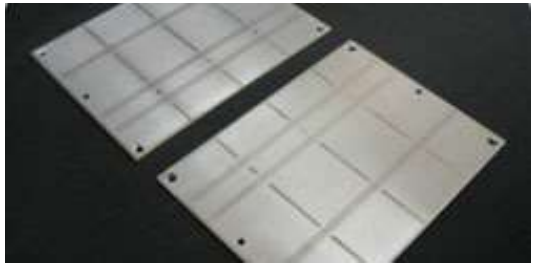


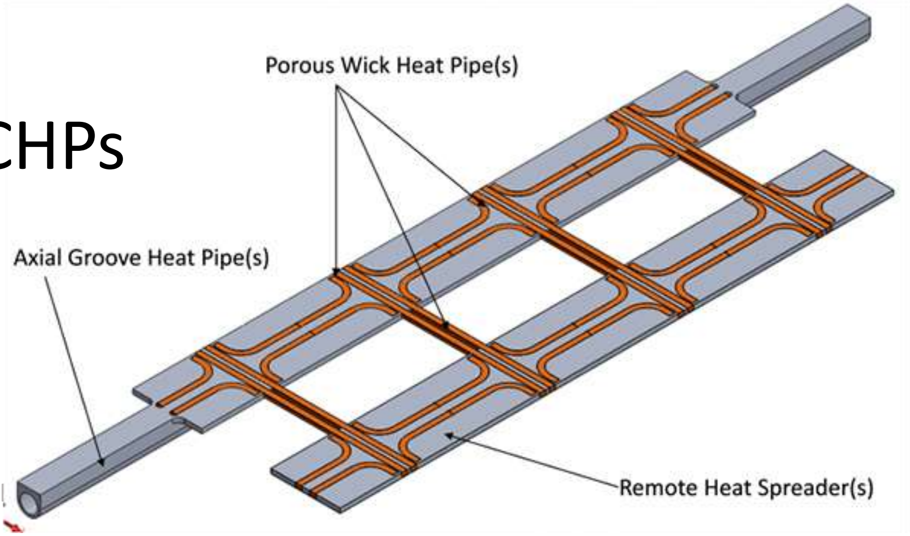
Response at ~950 cycles

Emerging Applications – Cu/H_2O Heat Pipes

- In combination with phase change material to provide uniform heat input (efficient melt)
- Allow radiators to be sized for **time-averaged** power instead of peak
- In combination/integrated into low CTE materials (WCu, AlSiC..) for CTE matched cooling
- Upstream of common Al-NH_3 CCHPs for reduced heat flux





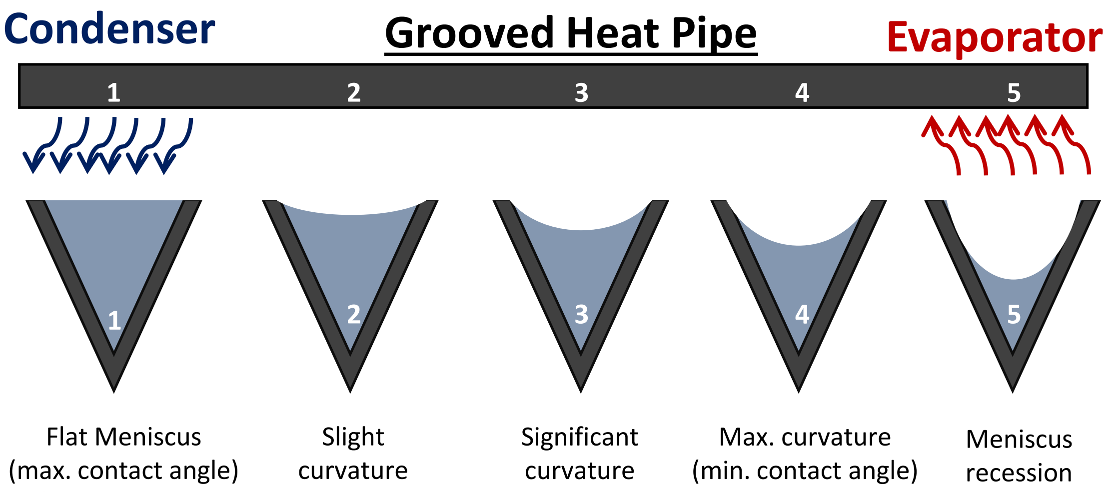


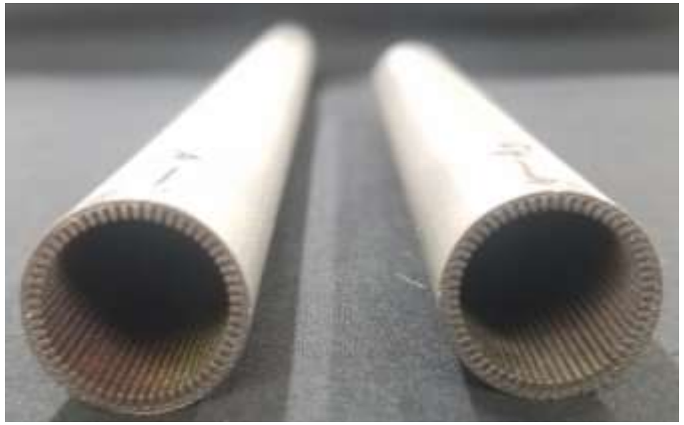
Higher Temperature Water Heat Pipes & Radiators

- Copper/Water heat pipes in space to date are generally used for short distances in electronics chassis
  - Screen or Sintered wick
  - Conduct heat to aluminum/ammonia CCHPs, or a Loop Heat Pipe, to deliver the heat to the radiator.
- Grooved water heat pipes can also be used for higher temperature radiators
  - Shrink the radiator substantially (T^4)
  - Copper is too heavy for long grooved heat pipes
  - Use Titanium/Water at temperatures up to 550K (270°C)
  - Life tests conducted by ACT for ~7 years show that it is compatible

Grooved Titanium/Water Heat Pipes for Space

- Can fabricate by EDMing, or by 3D printing
  - Trapezoidal grooves aid in freeze/thaw protection
- Sections joined together by EB welding
- Developed procedures for bending
- 3D printed pipe was leak-tight with an 0.39 mm (0.015 in.) wall thickness





3D Printed Above, EDMed below

Freeze/Thaw Tolerance for Grooved Water Heat Pipes

- Need to prevent damage when water freezes and expands
- Copper/water heat pipes discussed above have a porous wick
  - Prevent damage by controlling inventory to prevent liquid bridge
- Titanium/water heat pipes have a grooved condenser wick
- Evaporator Wick has a screened wick reservoir to hold water during freeze/thaw cycles
- For certain applications, want to allow pipes to go through several freeze/thaw cycles on the ground, with the condenser down
  - Add collapsible volume to allow limited freeze/thaw cycles

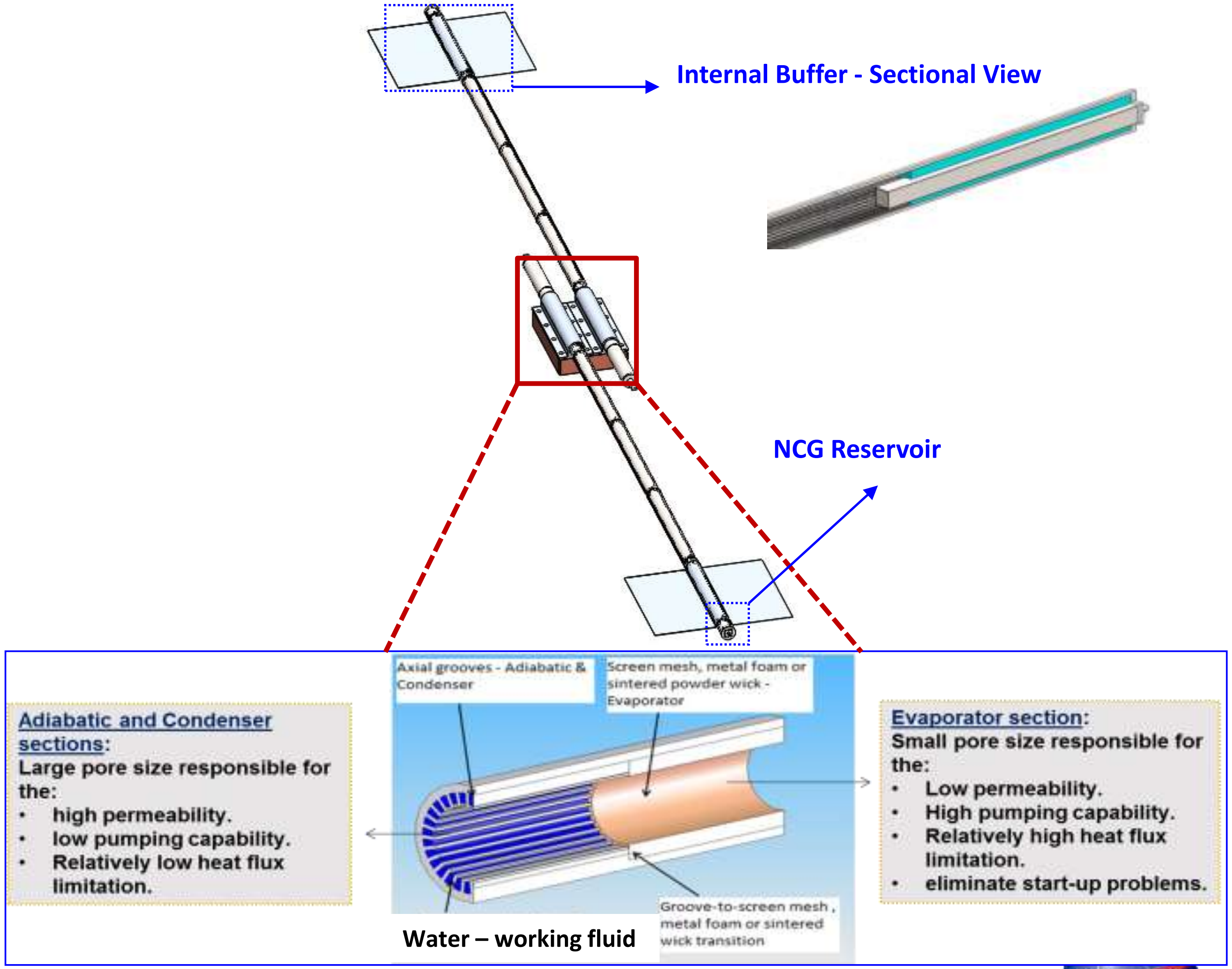
Freeze/Thaw Tolerance for Grooved Water Heat Pipes

- Grooved Heat Pipes need the following for freeze tolerance:

1. Trapezoidal Shaped Grooves
2. A small amount of Non-Condensable Gas (NCG), to allow the heat pipe to freeze/unfreeze gradually, without freezing water in the condenser
3. A supplemental wick (reservoir) near the evaporator, to hold excess water, and prevent it from freezing in the condenser.
4. A buffer in the condenser for storage on the ground to prevent freezing related problems if the condenser is down.

Lightweight Titanium Water Heat Pipes

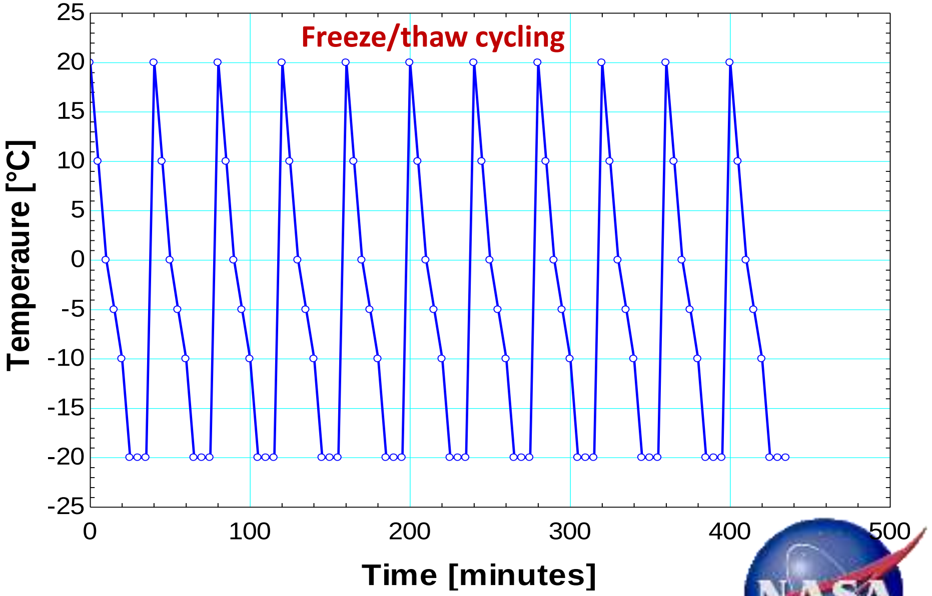
- Can use in higher temperature radiators, where too hot for Al/NH_3
- Developed lightweight grooved titanium/water heat pipes to operate at higher temperatures
  - Future GaN power amplifier devices will operate at temperatures in excess of 150 degrees C and will exceed power densities of 1400 W/cm^2 (600W over 0.635 cm x 0.635 cm).
  - Operate over the temperature range of 25 to 150 °C and must survive a temperature range of -60 to 150 °C.
- Add internal buffer in the condenser section to allow ~ 5 freeze/thaw cycles on earth



Freeze/thaw tolerance – Condenser side

- An innovative feature "the internal buffer" was designed in the condenser side to mitigate volumetric expansion of the fluid during freeze/thaw.
  - This feature damps the force exerted by ice as it freezes and expands.
  - The preliminary results show that using this internal buffer is promising for repeating many freeze/thaw cycles successfully.

The feature deforms elastically to damp the forces of freeze/thaw



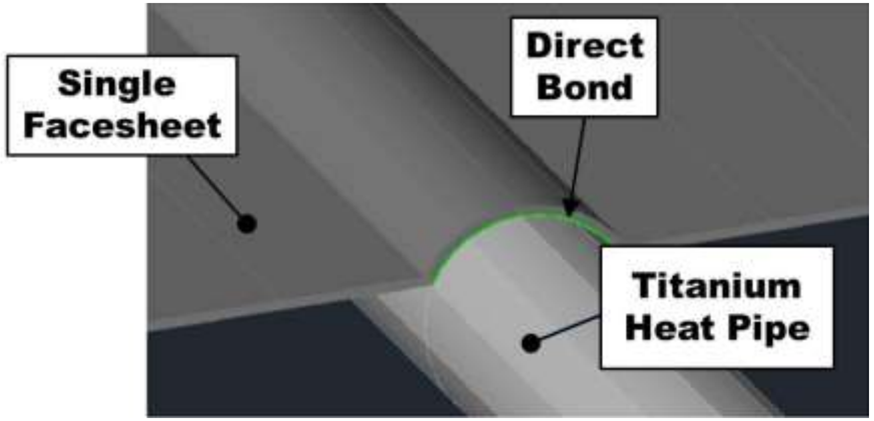
This Phase I SBIR program is sponsored by U.S. AF Research Lab under Contract No. FA9453-16-M-0446 KOM

Radiators for Titanium/Water Heat Pipes

- Aluminum/Ammonia CCHPs are directly bonded to aluminum facesheets, with an aluminum honeycomb to help provide rigidity
- Can't use aluminum facesheets with titanium heat pipes, due to the C.T.E. mismatch (Al: 24 10^{-6} m/(m K)) (Ti: 8.5 10^{-6} m/(m K))
- Use Graphite Fiber Reinforced Composite (GFRC) Facesheets
- Control the GRFC layup to match C.T.E.s along the heat pipe axis

Radiators for Titanium/Water Heat Pipes

- Originally added POCO foam saddles to accommodate the C.T.E. mismatch perpendicular to the heat pipe axis
  - During tensile testing, heat pipe failed before bond
- Concluded that could directly bond the titanium and GFRC



Water Heat Pipes in Space – Takeaways

- Benefits of Copper/Water Heat Pipes and HiK™ Plates
  - Operate at temperatures up to 150°C, versus 80°C for aluminum/ammonia heat pipes
  - Can be incorporated into electronics assemblies and reduce peak temperature or increase power
  - Complement aluminum/ammonia CCHPs
- 270°C for Titanium/Water (not flight tested)
  - Freeze in any orientation on Earth
  - Can be used for higher temperature radiators/electronics, reducing mass and size
- Qualification / Space Readiness
  - Freeze/Thaw and Shock/Vibe tolerant
  - TRL 9: Copper/Water heat pipes on current satellites

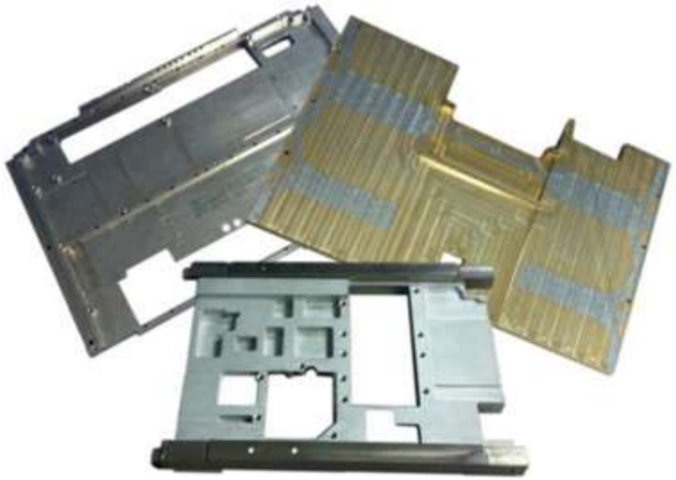
Copper/Water Heat Pipes for Embedded Computing

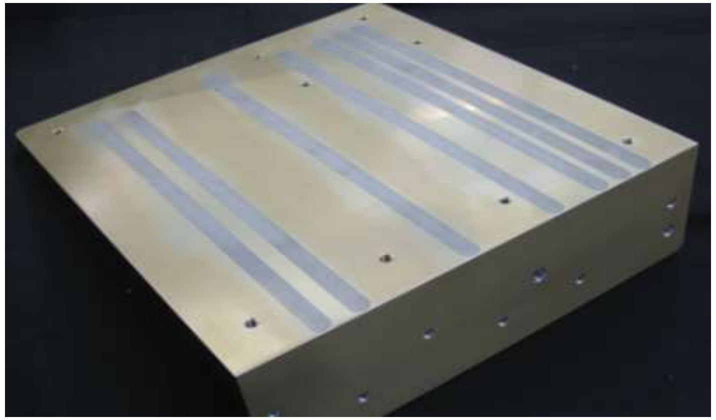
- Cards slide into an enclosure / chassis and are mechanically / thermally coupled with a retainer clamp
- For highest reliability, sealed enclosures are utilized
  - Environment Proof (Dust, Rain, etc.)
  - Results in conduction being a key contributor to thermal performance
- Standards exist for common architectures: VITA Specifications
- Passive cooling to "get heat out" is preferred. The ultimate heat sink is typically liquid base cooled or air cooled
- Spacecraft use CCHPs or LHPs and radiators

Image Courtesy of Industrial Embedded Systems Article. Oct 2008, PCI-Systems

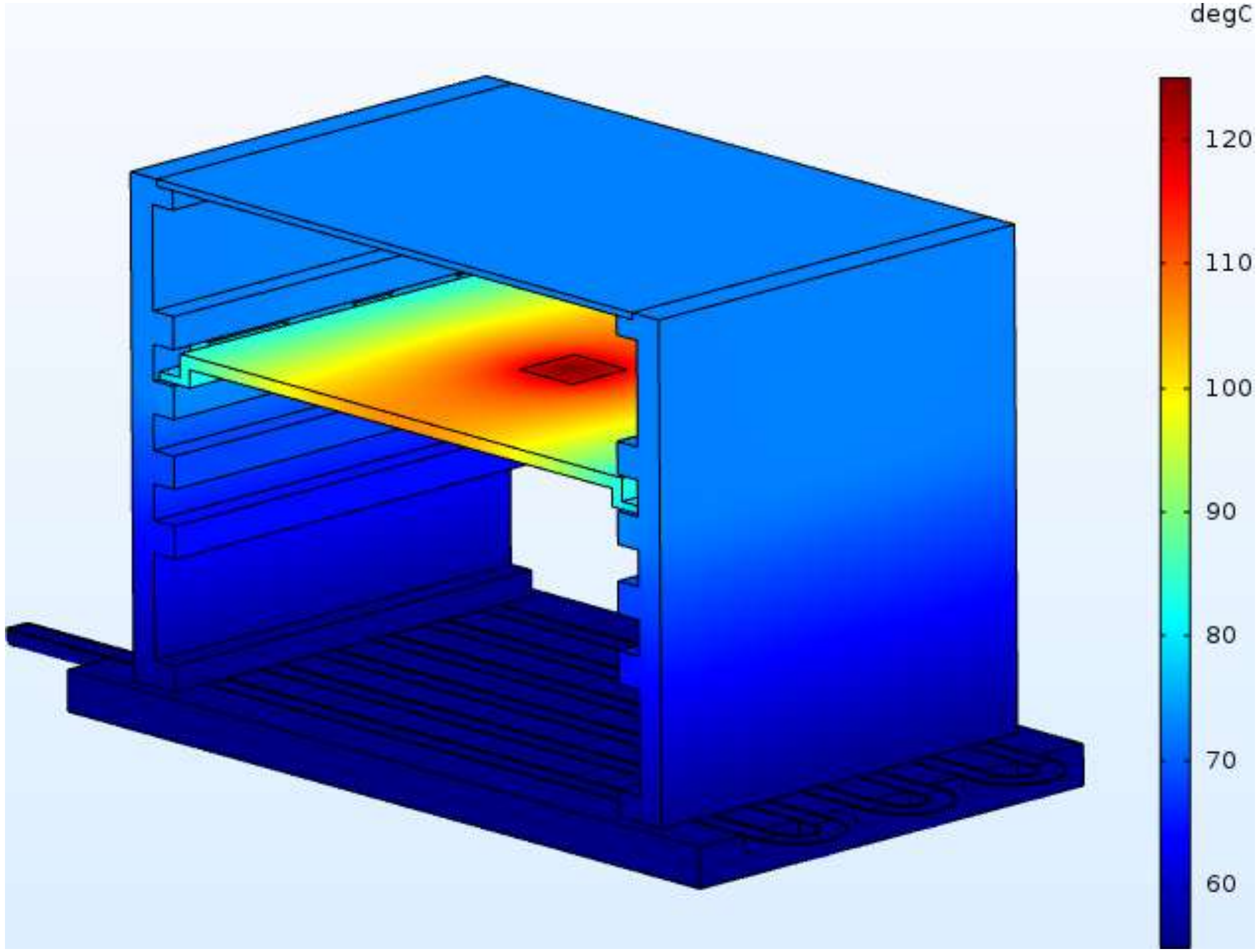
Board and Box Considerations

- HiK™ Board Frames
  - Transfers heat to edge/chassis
- ICE Lok™ Retainers
  - Reduces temperature rise from board to chassis
  - > 30% over COTS designs
- HiK™ Chassis / Sidewalls
  - Moves heat to the base
  - Lowers heat flux to high level thermal solution





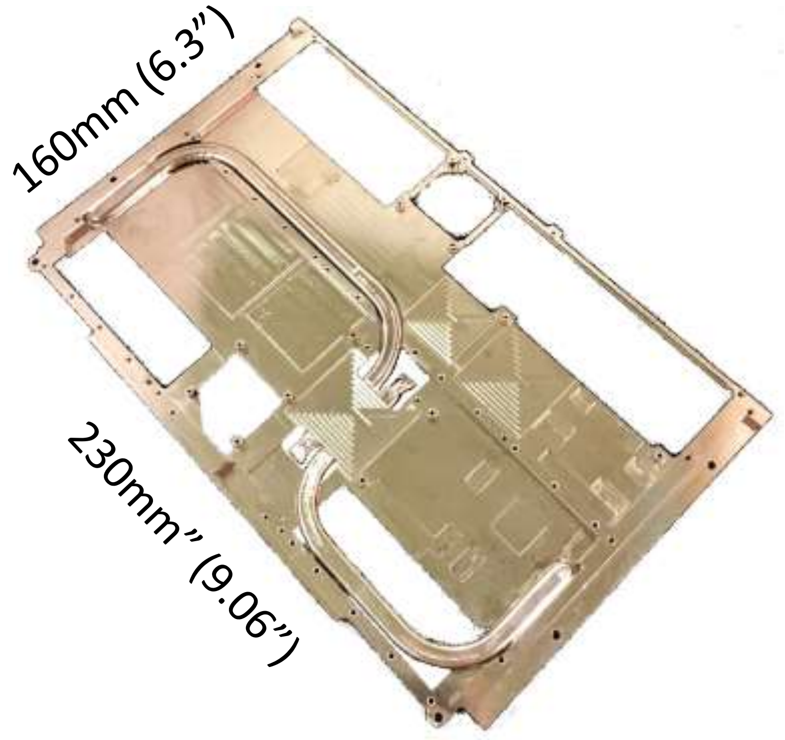
Case Study - Baseline



Item	Temperature (°C)
Cold Plate	55
Card Max	124
Card Min	77
Chassis Max	74
Chassis Min	55
Wedgelock Card Side	83
Wedgelock Chassis Side	73
Total Delta T	**69**

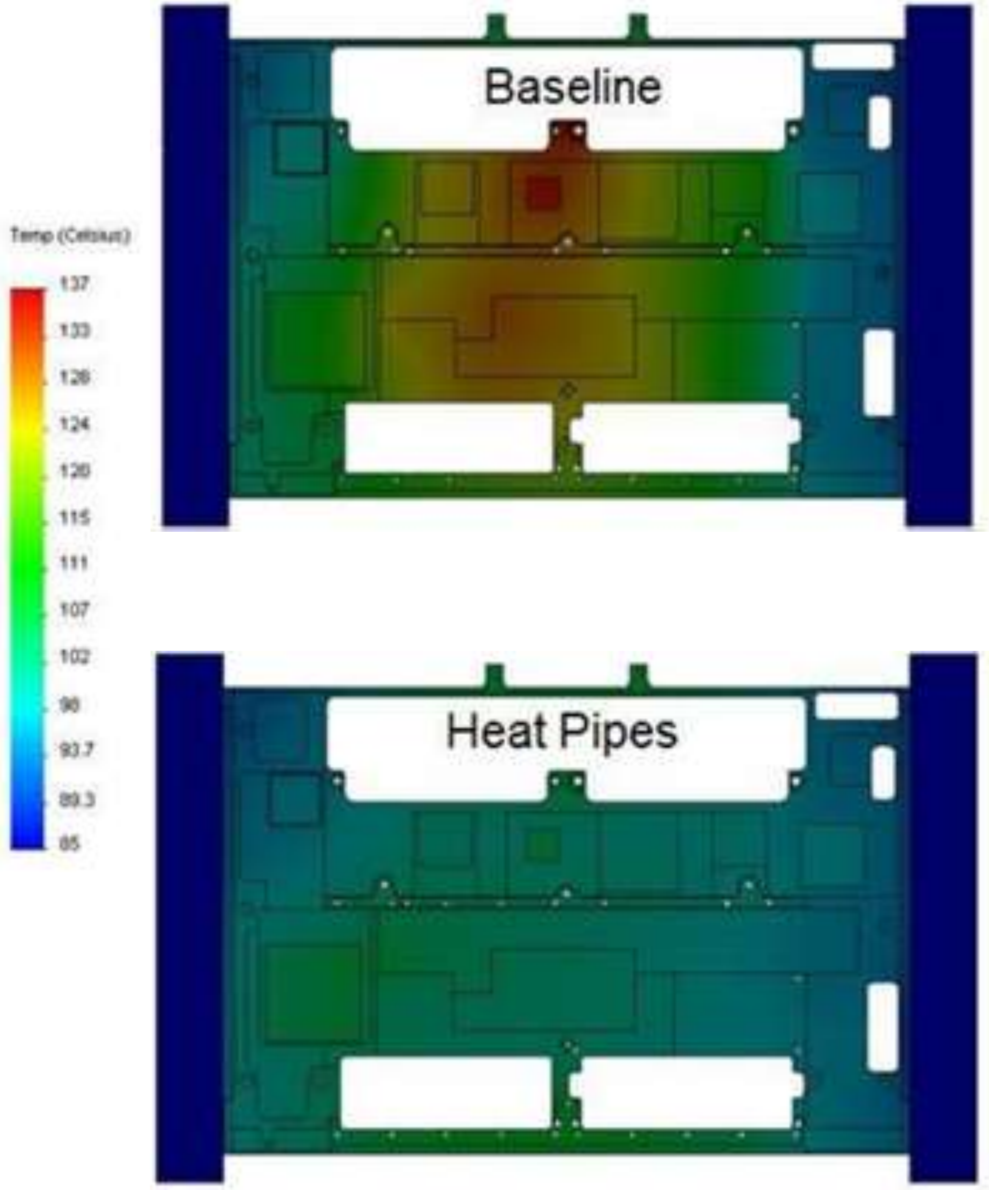
Resistance 1 – The Card Frame

- Aluminum provides a good combination of weight, strength and thermal conductivity
  - k = 167 W/m-K
- 6U board have a fairly long conduction path to the edge if critical components are placed near the center
- Due to the bottleneck at the edge, spreading heat along the edge to lower heat flux can significantly help reduce gradients

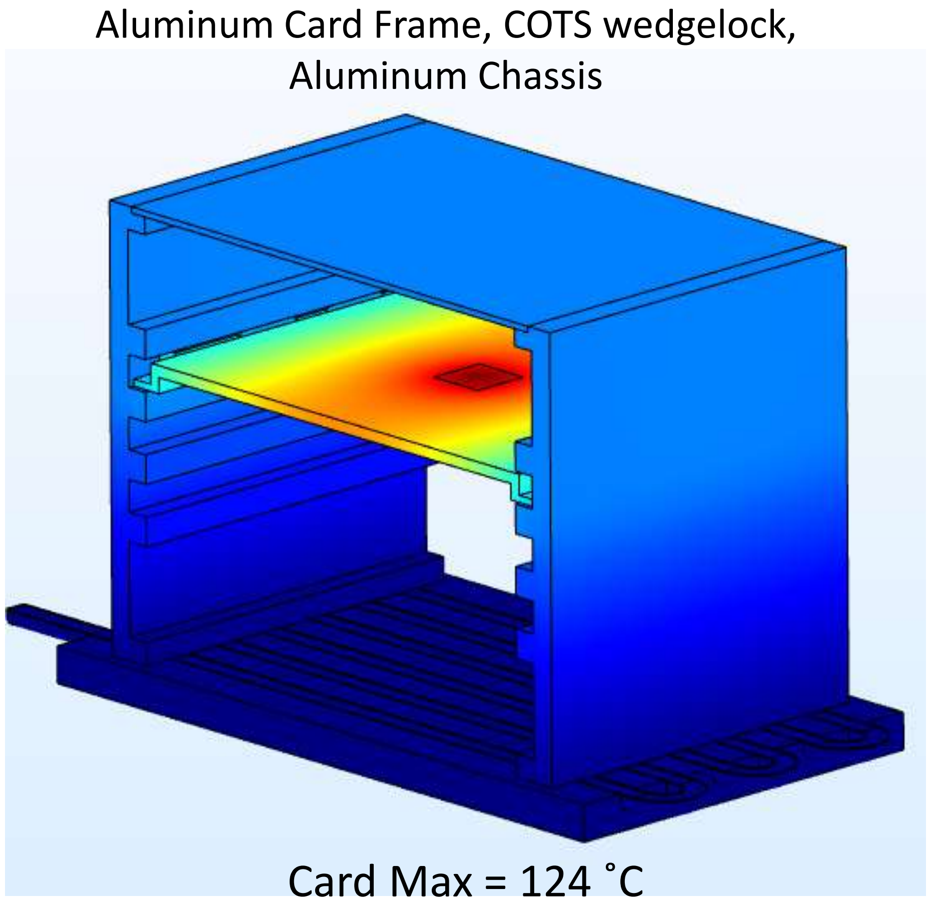


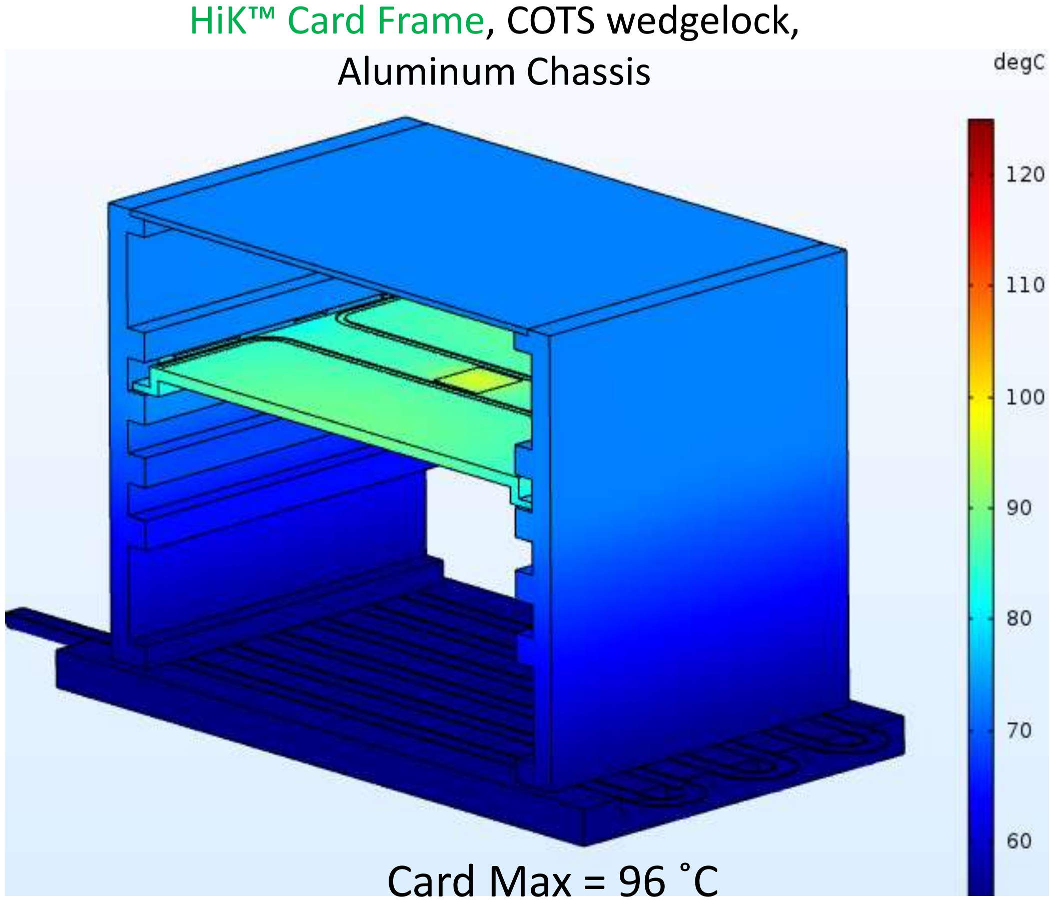
HiK™ Card Frames

- HiK™ = High Thermal Conductivity by embedding heat pipes in the aluminum frame
  - Aluminum Frame: k = 167 W/m-K
  - HiK™ Frame: k = 650 W/m-K (For 6U form factor)
- Similar Weight as Aluminum
- Similar Strength as Aluminum
- All critical features can be maintained

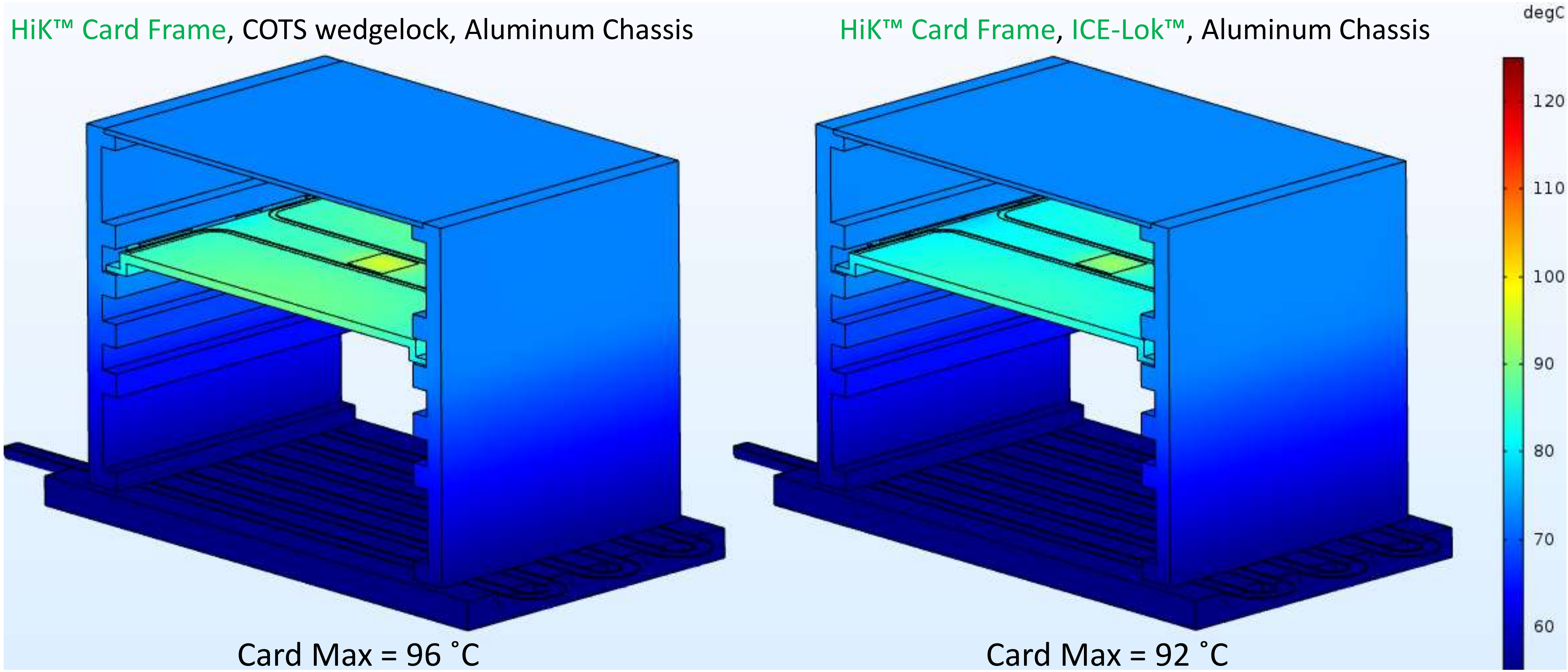


Case Study Before and After…

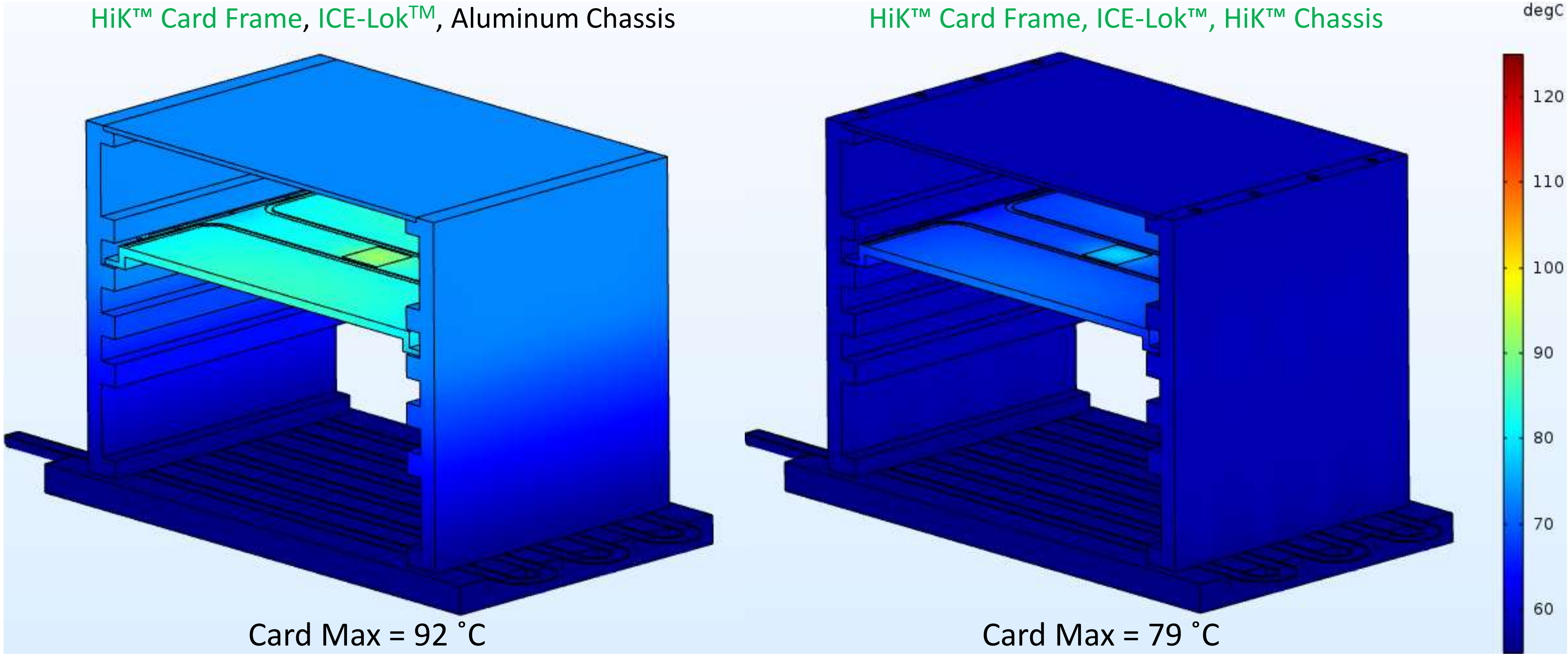




Case Study – With Enhanced Wedgelock

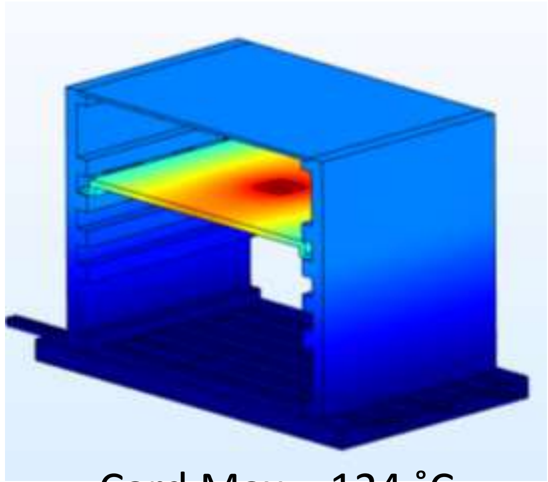


Case Study – Taking Heat from Bottom

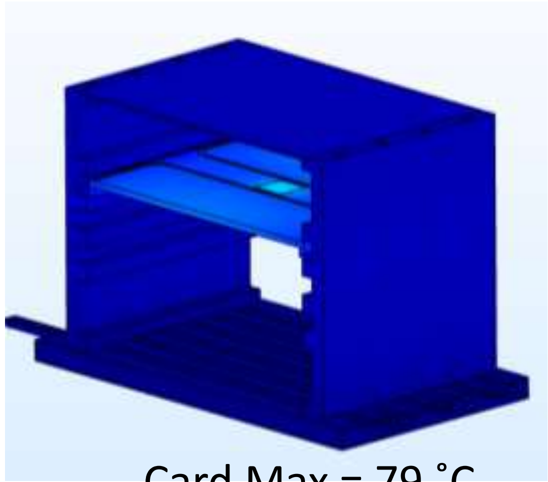


Takeaways – Heat Pipes for Embedded Computing

- Understanding the thermal resistance network is key to determining the best design option to fulfill thermal and programmatic objectives
  - HiK™ Card Frames will lower heat spreader conduction gradients
  - ICE-Lok™ will reduce temperature rise at the card/chassis interface
  - HiK™ Chassis can isothermalize or transport heat to the ultimate heat sink



Card Max = 124 ˚C



Card Max = 79 ˚C

Agenda

- ACT Introduction
- General Thermal Considerations
- Heat Pipe Basics
- Heat Pipe Limits
- Heat Pipe Applications
- Different Types of Heat Pipes
- Heat Pipe Working Fluids and Compatibility
- Heat Pipe Wicks
- Heat Pipe Modeling
- CCHP Design
- CCHP Manufacturing and Testing
- VCHPs for Variable Thermal Links
- Copper/Water Heat Pipe Design
- Copper/Water Heat Pipes in Space
- Copper/Water Heat Pipes in Embedded Computing
- Conclusions
- References
- Acknowledgements

Conclusions

- Spacecraft/Satellite thermal design is unique due to the temperature ranges, vacuum-like environment and lack of gravity
  - Radiators are more efficient at higher temperatures
- Reliability is key (we cannot send maintenance crews up to space!)
  - Passive Solutions are Preferred
- Aluminum/Ammonia CCHPs or Loop Heat Pipes are the standard for transferring heat from electronics to the radiator
  - Typically -60 to 40°C
- Copper/Water heat pipes being used in electronics boxes
  - Typically 25 to 150°C
  - Reduced ΔT from electronics to radiators decreases radiator size and mass
- Specialized heat pipes can maintain temperature, act as diodes

Heat Pipe References

- ACT Heat Pipe Resource Page, https://www.1-act.com/resources-/heat-pipe-resources/
  - Most complete collection of heat pipe resources available on the web
- ACT Heat Pipe Calculator, https://www.1-act.com/resources/heat-pipe-calculator/
- ACT Heat Pipe FAQ, https://www.1-act.com/innovations/heat-pipes/
- ACT Technical Papers, https://www.1-act.com/resources/tech-papers/
- ACT Webinars, https://www.1-act.com/act-webinars/
- Jentung Ku, "Introduction to Heat Pipes" Short Course, 2015 NASA TFAWS, https://tfaws.nasa.gov/files/TFAWS2015-SC-Heat-Pipes.pdf
  - https://tfaws.nasa.gov/files/TFAWS2015-SC-Loop-Heat-Pipes.pdf

Heat Pipe References

- Heat Pipe Basics:
  - Dunn and Reay, or Reay and Kew: Heat Pipes – best overall introduction
  - B&K: Heat Pipe Design Handbook
    - https://archive.org/details/nasa_techdoc_19810065690. (they were written in the 1970's for NASA – the theory hasn't changed at all).
  - Chi: Heat Pipes – Best for theory, may be hard to find
- Advanced:
  - Faghri: Heat Pipe Science and Technology: flooding, etc.
- PCHPs, VCHPs and Diode Pipes
  - Marcus, Theory and Design of VCHPs, written for NASA https://ntrs.nasa.gov/search.jsp?R=19720016303
  - ACT Technical Papers, https://www.1-act.com/resources/tech-papers/

Fluid Property References

- NIST Thermophysical Properties of Fluid Systems
  - http://webbook.nist.gov/chemistry/fluid/
  - Can export as graphs or charts
  - In addition to saturated fluid properties, can get data for subcooled liquids, and superheated gases
- NIST Refprop
  - Additional fluids compared to the NIST website
- Avoid using the tables in the older Heat Pipe Handbooks, if at all possible
  - Low order polynomial curve fits
- CRC Handbook of Chemistry and Physics
- Perry’s Chemical Engineer’s Handbook
- The Properties of Gases and Liquids – Poling, Prausnitz, & O’Connell

Acknowledgements

- Several figures were borrowed from a previous presentation by Jentung Ku from NASA Goddard:
  - Jentung Ku, “Introduction to Heat Pipes” Short Course, 2015 NASA TFAWS, https://tfaws.nasa.gov/files/TFAWS2015-SC-Heat-Pipes.pdf
  - There is also an excellent LHP presentation by Jentung at the 2015 NASA TFAWS, https://tfaws.nasa.gov/files/TFAWS2015-SC-Loop-Heat-Pipes.pdf
- ACT personnel who provided slides include Mohammed Ababneh, Darren Campo, Peter M. Dussinger, G. Yale Eastman, Bryan Muzyka, Pete Ritt, and Ryan Spangler.

TFAWS Heat Pipes Short Course

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Thermal & Fluids Analysis Workshop
TFAWS 2019
August 26-30, 2019
NASA Langley Research Center
Hampton, VA